JOINT EPA/NASA/USAF INTERAGENCY DEPAINTING STUDY

Sixth Progress Report

July 1998

National Aeronautics and Space Administration
George C. Marshall Space Flight Center

NOTICE

This material has been funded wholly or in part by Interagency Agreements among the U.S. Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA), and the U.S. Air Force (USAF). These agreements concern "Technical Assessment of Alternative Technologies for Aerospace Depainting Operations."

EXECUTIVE SUMMARY

The National Aeronautics and Space Administration (NASA) is conducting a technical assessment of alternative technologies for aerospace depainting operations on behalf of the Environmental Protection Agency (EPA) and the United States Air Force (USAF). Such technologies are to be used as paint stripping processes that do not adversely affect the environment and that specifically do not involve the use of methylene chloride.

During this reporting period, NASA was involved in the following activities:

- NASA personnel visited General Lasertronics Corporation to observe a carbon dioxide (CO_2) laser stripping system and welcomes General Lasertronics Corporation as a new committee member to assist with process evaluation.
- Personnel from the Environmental Protection Agency visited Marshall Space Flight Center (MSFC) for an in-depth program review of the interagency study.
- Control panels were painted, aged, and distributed for the third depainting sequence.
- During Sequence 3, four depainting processes (chemical stripping, FLASHJET®, plastic media blasting, and ENVIROSTRIP® wheat starch) were used on control panels. Sequence 3 data for the CO_2 laser, sodium bicarbonate wet stripping, and WaterJet processes will be available after the publication date of this report and will be presented in the final report.
- Interim measurements were made on the control panels for surface roughness, weight and thickness, and coating thickness. No significant changes in surface roughness measurements were seen after Sequences 2 and 3. Post-stripping surface roughnesses decreased slightly, probably a result of the presence of less remnant primer from the mechanical processes as operator skills improved.
- The control panels for chemical stripping, plastic media blasting, FLASHJET®, and ENVIROSTRIP® wheat starch were reprocessed, which included cleaning, chromate conversion coating, priming, and painting.
- A method of loading thin specimens into the fatigue tester was developed to allow fatigue testing of specimens without twisting. Baseline data collection resumed for fatigue life comparisons.
- Further analysis was performed on sandwich corrosion specimens to evaluate the extreme effect of deionized water.
- Hydrogen embrittlement effects of the environmentally advantaged chemical strippers on high-strength steel were determined.
- This progress report was published in July 1998.

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- The USAF's Materiel Command and Corrosion Control Laboratory, as well as Cape Canaveral Air Station, Davis Monthan Air Force Base (AFB) (including Aerospace Maintenance and Regeneration Center), Robins AFB (including Warner Robins Air Logistics Center), and Tinker AFB
- The U.S. Army Depot at Corpus Christi
- The U.S. Coast Guard

as well as to our Technical Advisory Committee and other members of private industry, including:

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The Boeing Company
CAE Electronics, Ltd.
Carolina Equipment
Delta Airlines
Duncan Aviation
Garrett Aviation
Grumman Aerospace
Hamilton Standard
General Lasertronics Corporation
Lockheed-Martin Space Operations
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Northrop Grumman
Raytheon Aerospace
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3M Corporation
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Amax Industrial Products Group
ARCO Chemical Company
Autre Products, Ltd.
BIX Processing Systems
Brulin Corporation
CAE Electronics, Ltd.
Calgon Corporation
Carolina Equipment
ColdJet
Diversey Corporation
Dynacraft Industries
Ecolink, Inc.
Eldorado Chemical Company
Fine Organics Corporation
Gage Products Company
INTA
International Specialty Products
ManGill Chemical Company
Maxwell Laboratory
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Orchem, Inc.
Pratt & Whitney
PyRock Chemical
Savogran Company
Silicon Alps
S&S Carbonic Industries
Titan Abrasive Systems
TOMCO$_2$ Equipment Company
Turco Products, Inc.

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Acronyms and Abbreviations

AMS	Aerospace Materials Specification
A	Ampere
CO_2	Carbon dioxide
cm	Centimeter
EDM	Electro-Discharge Machine
ESC	Electron Spectroscopy for Chemical Analysis
deg	Degree
ft	Foot
g	Gram
gal	Gallon
gpm	Gallons per minute
hr	Hour
HR_C	Rockwell hardness C
Hz	Hertz
IA	Interagency Agreement
IACS	International Annealed Copper Standard
in.	Inch
J	Joule
kg	Kilogram
ksi	Thousand pounds per square inch
ksi√in.	Thousand pounds per square inch times square root inch (fracture toughness unit)
kW	Kilowatt
L	Liter
lb	Pound
LN_2	Liquid nitrogen
mg	Milligram
mil	One-thousandth of an inch
MIL-	Military specification
min	Minute
mL	Milliliter
mm	Millimeter
MPa	Million Pascals
n/a	Not applicable
NESHAP	National Emission Standard for Hazardous Air Pollutants
oz	Ounce
PEL	Permissible Exposure Level
pH	Hydrogen-ion concentration
PMB	Plastic Media Blasting
ppm	Parts per million
psi	Pounds per square inch
sec	Second
-T#	Temper number
V	Volt
x	Times (magnification level)

Organizations

ADM	Archer Daniels Midland Company
AFB	Air Force Base
AISI	American Iron and Steel Institute
ASTM	American Society for Testing & Materials
CAE	CAE Electronics, Ltd.
EH01	MSFC Materials and Processes Laboratory
EH12	MSFC Physical Science and Environmental Effects Branch
EH22	MSFC Metallurgical Engineering Branch
EH23	MSFC Metallurgy Research and Development Branch
EH33	MSFC Nonmetallic Processes Branch
EH42	MSFC Environmental and Analytical Chemistry Branch
EPA	Environmental Protection Agency
IATA	International Air Transport Association
ISO	International Standards Organization
ITT	Illinois Institute of Technology
MDA	McDonnell Douglas Aerospace (now Boeing-St. Louis)
MSFC	Marshall Space Flight Center
MTS	MTS Systems Corporation
NAS	Native American Services, Inc.
NASA	National Aeronautics and Space Administration
OSHA	Occupational Safety and Health Administration
SAE	Society of Automotive Engineers
TAC	Technical Advisory Committee
TIC	Technical Implementation Committee
USAF	United States Air Force

Symbols

~	Approximately
$<$	Less than
$>$	Greater than
≤	Less than or equal to
≥	Greater than or equal to
+	Plus
–	Minus
±	Plus or minus
÷	Divided by
#	Number
°	Degree
°C	Degree Celsius
°F	Degree Fahrenheit
µin.	Microinch
µsec	Microsecond
%	Percent
R	Minimum ÷ maximum load
R_a	Arithmetic mean roughness value
®	Registered trademark
™	Trademark

Elements

As	Arsenic
C	Carbon
Cd	Cadmium
H	Hydrogen
N	Nitrogen
Na	Sodium
O	Oxygen

1.0 INTRODUCTION

1.1. Background

The National Aeronautics and Space Administration is conducting a technical assessment of alternative technologies for aerospace depainting operations in a cooperative effort with the Environmental Protection Agency and the U.S. Air Force. This interagency study was designed to evaluate an array of depainting processes that do not use methylene chloride, a probable carcinogen that is the active ingredient in many popular and widely used paint stripping products. The nine techniques subdivide into five removal method categories (abrasive, impact, cryogenic, thermal, and molecular bonding disassociation). Seven techniques are currently being investigated as alternatives to the use of methylene chloride.

The use of methylene chloride has been restricted in depainting operations per the National Emission Standard for Hazardous Air Pollutants (NESHAP) for Aerospace Manufacturing and Rework Facilities. The effective date of Maximum Achievable Control Technology regulation was September 1995, with the first substantive compliance date for existing sources being September 1998.

Industrial concerns may also wish to consider substituting another paint stripping process for methylene chloride to avoid compliance costs associated with a new standard adopted by the Occupational Safety and Health Administration (OSHA), which sharply limits permissible exposure levels (PELs) for workers. Employers must ensure that no employee is exposed to an airborne concentration of methylene chloride as an 8-hour time-weighted PEL in excess of 25 ppm or a 15-minute short-term exposure level in excess of 125 ppm, whereas the previous PEL was 500 ppm. The final rule includes requirements for exposure monitoring, medical surveillance, and respiratory protection. It was adopted on January 10, 1997, and put into effect on April 10, 1997.

1.2. Scope of Study

These tests were designed to be conducted on one paint system (epoxy primer in accordance with MIL-P-23377F, Type 1, Class 2, with a polyurethane topcoat, originally MIL-C-83286B but now MIL-C-85285B) applied to two substrate materials (clad and non-clad 2024-T3 aluminum in four thicknesses), processed in accordance with draft 4 of the International Standards Organization/Society of Automotive Engineers (ISO/SAE) MA4872, "IATA Guidelines for Evaluation of Aircraft Paint Stripping Materials and Processes." (See excerpt in Appendix A.1.) The specimens were then to be depainted under controlled conditions.

The results presented here are representative of this particular test protocol. Changing the processing and depainting parameters may yield different results, even on the same substrate and paint system. This report should be used as a guidance document when selecting an alternative depainting method, as it does not recommend any one depainting method over another. End users should consider the maturity of their facilities, equipment, and personnel training when analyzing process applicability for their operations.

1.2.1. Materials Selection

This study uses materials, coatings, and processes found in ISO/SAE MA4872 (draft 4), including other standards referenced under Section 2.0, Applicable Documents, in that draft. To ensure manageable parameters and data comparable to those available on similar substrates, NASA, the EPA, and the concerned industrial partners known as the Technical Advisory Committee (TAC) agreed to limit this study to one coating system on two substrate materials, as discussed below.

As referenced in the rest of this report, "Sequence 3" is used to designate the third iteration of activity (including processing, artificial aging, and depainting of the control panels, followed by data evaluation) that was conducted for this study.

1.2.1.1. Coating System

Plans called for use of the baseline paint system referenced in ISO/SAE MA4872 (draft 4), which is comprised of a high-solvents polyurethane topcoat, gloss finish, white #17925 (in accordance with MIL-C-83286B) applied over an epoxy primer (in accordance with MIL-P-23377F, Type 1, Class 2). These coatings exceed limits established in the Aerospace NESHAP, but they were partnered as a preferred paint system for many years, building a strong database of performance information.

The MIL-C-83286B topcoat, however, became unavailable after the processing of panels for Sequence 1. It has been replaced with a high-solids aliphatic polyurethane coating (in accordance with MIL-C-85285B). The Aerospace NESHAP does not require any changes for the high-solids epoxy primer (in accordance with MIL-P-23377F, Section 1.2). This revised paint system was incorporated at the beginning of Sequence 2 and is being used throughout the remainder of the study. (See Table 1.2.1.1-1.)

Table 1.2.1.1-1. Substrate Coating System

Surface Treatment	Primer	Topcoat
Iridite 14-2	MIL-P-23377F, Type 1, Class 2 (0.6 to 0.9 mil)	MIL-C-85285B (1.7 to 2.3 mil)

1.2.1.2. Test Substrates

The substrate material is 2024-T3 aluminum (clad and non-clad) in four thicknesses: 0.016, 0.032, 0.051, and 0.064 inches. Substrate requirements are detailed in SAE Aerospace Materials Specification (AMS) 4041, “Sheet and Plate,” and AMS 4037, "Aluminum Alloy Sheet and Plate." (See Table 1.2.1.2-1.)

Table 1.2.1.2-1. Control Panels (Initial Material)

Material	Specification	Thickness	Quantity
Clad 2024-T3 aluminum	AMS 4041 or Federal QQ-A-250/5	0.016 in.	3
		0.032 in.	3
		0.064 in.	16
Non-clad 2024-T3 aluminum	AMS 4037 or Federal QQ-A-250/4	0.016 in.	21
		0.051 in.	16
		0.064 in.	16

In addition, Sikorsky Aircraft Corporation provided 80 panels of clad 2024-T3 aluminum in two thicknesses. (See Table 1.2.1.2-2.) The processes using these clad panels are the in-house processes: plastic media blasting (PMB), WaterJet blasting, and sodium bicarbonate wet stripping. Data from PMB clad panels appear in this report. The chemical stripping process had included 0.064-inch thick clad panels for evaluation from the beginning, and because panel thickness is irrelevant for chemical stripping, no Sikorsky panels were added to this process.

Table 1.2.1.2-2. Control Panels (Additional Clad Material)

Material	Specification	Dimensions	Thickness	Quantity
Clad 2024-T3 aluminum	Federal QQ-A-250/5	22 in. wide by 22 in. long	0.016 in.	40
			0.032 in.	40

1.2.2. Sample Preparation

Initially, the specimens were cut to appropriate sizes and uniquely numbered, so that they could be tracked throughout the study. Then, several preparation steps were used to develop the baseline data. (See Table 1.2.2-1.)

Table 1.2.2-1. Initial Sample Preparation

Step	Action
1	Hand-wipe specimens with methyl ethyl ketone.
2	Clean specimens, *i.e.*, degrease, alkaline clean, rinse with deionized water, deoxidize, final rinse with deionized water.
3	Apply chromate conversion coating (Iridite 14-2).
4	Measure baseline substrate thickness.
5	Measure baseline surface roughness and weights.

Standard ISO/SAE MA4872 (draft 4) requires five depainting sequences, each of which begins with the application of primer. From this point, a sequence includes the process details listed in Table 1.2.2-2.

Table 1.2.2-2. Sequence Activities

Step	Action
1	Apply primer.
2	Apply topcoat and cure at 122 ±5 °F for 24 hr.
3	Verify coating thickness.
4	Age specimens.
5	Distribute specimens to be stripped by methods under review.
6	Hand-wipe specimens with methyl ethyl ketone.
7	Clean specimens, *i.e.*, degrease, alkaline clean, rinse with deionized water, deoxidize, final rinse with deionized water.
8	Apply chromate conversion coating (Iridite 14-2).
9	Measure substrate thickness.
10	Measure surface roughness and weights.

Each step is in accordance with the procedures outlined in ISO/SAE MA4872 (draft 4).

1.2.3. Artificial Aging

NASA, the EPA, and the TAC selected an aging sequence in compliance with the version of ISO/SAE MA4872 available at that time, *i.e.*, draft 4, which has been superseded by four drafts. The TAC industry partners strongly suggested that this study closely follow the parameters provided in Appendix C of that document, which describes an intense aging scenario. (See Table 1.2.3-1.)

Table 1.2.3-1. Aging Procedure for Test Substrates per ISO/SAE MA4872 (Draft 4)

Step	Action
1	Precondition for 12 hr at 120 °F and 95% relative humidity.
2	Hold at -65 °F for 1 hr.
3	Thermally cycle aging chamber 400 times, each time cycling from -65 to 160 to -65 °F within 30 min.
4	Return aging chamber to ambient temperature.
5	Repeat steps 1 through 4.

Specimens are being aged in two thermal humidity chambers at MSFC. NASA was unable to meet the temperature ramp in 30 to 50 minutes (step 3) with a full aging chamber; therefore, the EPA and the TAC agreed to age specimens at the fastest rate that would allow them to be exposed to the temperature extremes defined in the aging profile. All participants indicated that they understood that the overall study timeline would be greatly impacted by this aging procedure, which proved quite lengthy. Ramifications included:

- During initial aging sessions, each temperature cycle required 3 hours to complete (rather than the specified 30 minutes), which resulted in a 97-day aging sequence.
- In May 1996, liquid nitrogen (LN_2) cooling lines were run to two thermal humidity chambers used for aging. This modification increased cooling rates by ~60% and reduced temperature ramp times by ~40%. Each temperature ramp now requires 1.5 hours to complete, which has resulted in a 51-day aging sequence.

1.2.4. Process Evaluation

When considering the results discussed in this report, the reader should bear in mind that many restrictions were required to maintain a manageable scope for our study.

Evaluation of the alternative methods will be determined through (1) analysis of results from measurements made on substrate thickness and weight, surface roughness, and surface chemical analysis throughout the sequences of preparation and stripping, (2) comparison of strip rates among the observed methods, and (3) further metallurgical evaluations of the substrate after final sequences of specimen preparation and stripping.

1.2.5. Schedule

The original scope of work and statement of tasks call for extensive and detailed data capture during each step of specimen preparation and stripping for all five depainting sequences. The revised project scope entails five full depainting sequences for the chemical stripping process, four full cycles for PMB, and three full cycles for the FLASHJET®, CO_2 laser, sodium bicarbonate wet stripping, WaterJet, and ENVIROSTRIP® wheat starch procedures. The projected schedule takes the depainting evaluation activities through the 1998 calendar year. (See Table 1.2.5-1.) The final report will contain all remaining data, as well as metallurgical evaluations of the processes. This report will be published in January 1999.

Table 1.2.5-1. Depainting Study Schedule

Action	Date
EPA/NASA Interagency Agreement (IA) signed	12/93
Executive Steering Task Force formed	2/94
Technical Implementation Committee (TIC) formed	2/94
First progress report published	8/94
USAF/NASA IA signed	9/94
Second progress report published	4/95
Test specimens acquired and machined	3/95 to 8/95
Third progress report published	10/95
EPA/NASA IA Amendment I signed	11/95
Depainting Sequence 1	8/95 to 5/96
Fourth progress report published	11/96
EPA/NASA IA Amendment II signed	9/96
Depainting Sequence 2	6/96 to 5/97
Fifth progress report published	11/97
Depainting Sequence 3	1/97 to 7/98
Sixth progress report published	7/98
Remainder of stripping sequences	6/97 to 10/98
Metallurgical specimens machining	5/98 to 9/98
Metallurgical evaluation	6/98 to 11/98
Data compilation and analysis	8/98 to 12/98
Final report published	1/99

2.0 SITE VISITS

2.1. Hydrogen Peroxide Exposure Tests

The Hydrogen Peroxide Exposure Testing study is designed to determine whether certain concentrations of hydrogen peroxide actually cause corrosion or brightening of the aluminum surface as described in this progress report. Results of the initial gross test for hydrogen peroxide corrosion on the specified aluminum surfaces were inconclusive because similar surfaces gave inconsistent surface roughness data. Also, the metallographic camera produced visual data based how the test specimens were cut. The test is being reconfigured to improve control over the cutting of the sample and to identify the surface side. The reconfigured test will enable collection of pretest surface roughness and metallographic camera data for posttest comparisons.

The MSFC point of contact is EH42/Jimmy Perkins at (256) 544-2634.

2.2. General Lasertronics Corporation

On June 12, 1997, Steve Burlingame made a trip to General Lasertronics Corporation, then located in Milpitas, California. The purpose of his trip was to set up an agreement whereby Lasertronics would assume the CO_2 laser stripping responsibilities previously held by INTA of Santa Clara, California. General Lasertronics Corporation was chosen as the most likely candidate for continuing the remaining CO_2 laser stripping cycles because the company is familiar with our requirements; is currently developing, manufacturing, and selling laser coating removal systems; has personnel experienced in engineering, manufacturing, and marketing with experience in aerospace, simulation, electronics, and optics; and has commitment to help this EPA/NASA/USAF Depainting Study meet its objectives.

Burlingame met with Phil Barone/President, Ralph Miller/Director, Marketing Communications, and Jim Thomas/Vice President, Engineering. He was given a detailed overview of both Lasertronics' coating removal capabilities and the experience of their personnel, and he toured the laser stripping facility and observed their stripping operations, which are similar to those that will be used to strip the aluminum test panels. The company accepted a letter of intent from Dr. Ann Whitaker/Director of the Materials and Processes Laboratory and will participate in this study by assisting in meeting the requirements of the study's technical objectives.

This study team thanks INTA for their participation and notes that the pursuit of another company to complete the CO_2 laser stripping cycles was driven by scheduling issues, not by technical concerns.

2.3. EPA Visit

In September 1997, Al Wehe and Barbara Driscoll, who, at the time, were EPA co-leads for the Interagency Agreement, visited Marshall Space Flight Center. During this "Depainting Project Review," MSFC personnel provided the EPA visitors with a comprehensive status of the study. This status included a discussion of the overall scope of the study and the decision process in determining that scope, a review of the sequence of events in each iteration of stripping required of the panels, a current status of the panels tagged to each process, a review of the interim measurements required and their purpose, an overview of all metallurgical evaluations to be performed and a status of those activities, and detailed discussions of schedule, cost, and aging issues.

The EPA guests also toured the MSFC facilities. This tour included the cleaning facility, the paint shop, the aging chambers, and the equipment setup for in-house stripping activities, with demonstrations of certain stripping processes. (See Figures 2.3-1 through 2.3-5.)

Figure 2.3-1. Jeneene Sams, Robin Broad, Johnnie Clark, Barbara Driscoll, Al Wehe, and Beth Cook (l to r) observe one of the panel cleaning vats in the MSFC cleaning facility.

Figure 2.3-2. Wehe tries his hand at plastic media blasting.

Figure 2.3-3. Cook, Clark, Wehe, Driscoll, and Sams observe the fan nozzle used in the sodium bicarbonate depainting technique. David Hoppe holds the nozzle.

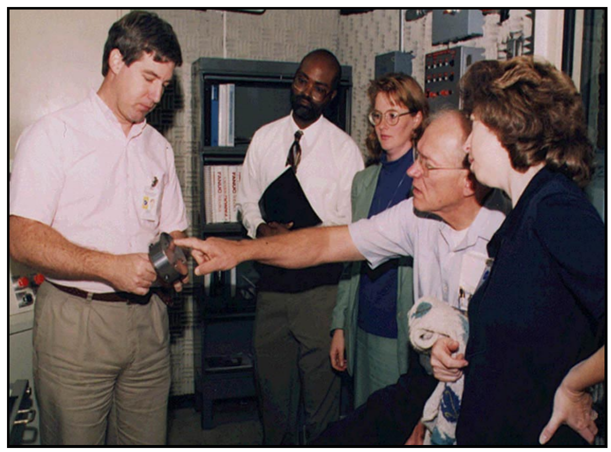


Figure 2.3-4. Hoppe (left) shows the Hammelmann rotary nozzle, used in the WaterJet stripping technique, to Clark, Broad, Wehe, and Driscoll.

Figure 2.3-5. Driscoll inspects a panel stripped with the WaterJet method. The patterns on the panel are produced as water from the nozzle blasts the topcoat and primer off the panel.

3.0 ACTIVITIES DURING SEQUENCE 3

3.1. Sample Preparation and Aging

Cleaning and coating activities were completed for 175 control panels, which were aged in four batches in preparation for depainting during Sequence 3. (See Table 3.1-1.)

Table 3.1-1. Aging Schedule

Batch	Aging Duration	Control Panels for Use in	Quantity
1	3/4/97 to 4/28/97	Chemical Stripping	50
		CO_2 Laser Stripping[1]	9
2	3/31/97 to 5/27/97	Plastic Media Blasting	29
		Sodium Bicarbonate Wet Stripping	9
3	4/28/97 to 6/23/97	WaterJet Blasting	24
4	5/27/97 to 7/2/97	FLASHJET® Coating Removal[2]	24
		ENVIROSTRIP® Wheat Starch Blasting	30

Notes: 1. One of the original 10 panels remains at the former vendor's facility.
2. One of the original 25 panels was used to assess the effects of overheating during processing.

3.2. Depainting Processes

This study is being conducted on chemical strippers that do not contain methylene chloride and on six mechanical stripping processes: FLASHJET® coating removal, CO_2 laser stripping, plastic media blasting, sodium bicarbonate wet stripping, WaterJet blasting, and ENVIROSTRIP® wheat starch blasting. All test fixtures include aluminum backing plates for the 0.016-inch substrates, which are extremely thin and flexible.

After Sequence 1, the TAC decided to eliminate two CO_2 blasting processes (TOMCO$_2$ and COLDJET™) from the study. After Sequence 2, the TAC pursued CO_2 laser stripping with a new vendor to optimize logistics. (See Section 3.2.4.)

The study's scope is limited to one coating system on two substrates to obtain results in a timely manner that could provide the most benefit to facilities that depaint aerospace hardware. A test protocol encompassing different paint systems or processing and operating parameters may yield different results.

3.2.1. Chemical Stripping

During the third depainting sequence, this process was used to strip 50 control panels cut from clad and non-clad 2024-T3 aluminum sheets (0.064 inch thick). Four alkaline/neutral products (Gage Stingray 874B and Turco 6813, 6813-E, and 6840-S) and four acid products (Turco 6776, McGean-Rohco Cee-Bee E-1004B, Calgon EZE 540, and Eldorado PR-2002) were tested alongside two methylene chloride strippers (McGean-Rohco alkaline Cee-Bee R-256 and acid Cee-Bee A-202), which acted as baselines. The aforementioned chemical strippers will be tested for the remainder of the study.

The chemical stripping investigators have adopted the basic procedure observed during a site visit to Raytheon (discussed in Section 2.1 of the *Fourth Progress Report*), which will be used for the remainder of the study. The strippers were initially applied in a thin mist, followed by a slightly heavier mist approximately 30 minutes later. The paint surface was checked approximately every 2 hours. If any paint showed release, the panel surface was lightly brushed using a brass bristle brush, and then the stripper was reapplied in the same manner. Temperatures were kept within a range of 75 to 82 °F, with an average relative humidity of 36%. (See Table 3.2.1-1.)

Table 3.2.1-1. Test Parameters for Chemical Stripping (Sequence 3)

Substrate Thickness (in.)	**Application Method**	**Depainting Facility Temperature** (°F)	**Average Relative Humidity**
0.064	Spray or brush on	75 to 82	36%

All chemical strippers removed 100% of the paint system from these control panels. (See Table 3.2.1-2.) Detailed results are discussed below and in Appendix A.2.1.

Table 3.2.1-2. Average Results for Chemical Stripping (Sequence 3)

Chemical Type	**Approximate Dwell Time** (hr)	**Post-Stripping Surface Roughness** (μin.)	**Coatings Removed**
Alkaline/Neutral	4	10.2	100% topcoat and 100% primer
Acid	3	10.1	

Note: These averages do not include any baseline data from the two methylene chloride strippers.

During Sequence 3, all chemical strippers had dwell times that were similar to those seen in a comparison with Sequence 2 data. (See Tables 3.2.1-3 and 3.2.1-4.)

Table 3.2.1-3. Average Test Data for Alkaline/Neutral Strippers (To Date)

Chemical Product	Average Dwell Time per Sequence			Average Surface Roughness (µin.)						
				Baseline	After Stripping			After Cleaning		
	Seq. 1	Seq. 2	Seq. 3	Measure-ment	Seq. 1	Seq. 2	Seq. 3	Seq. 1	Seq. 2	Seq. 3
Cee-Bee R-256[1]	30 min	7 min	5 min	1.2	1.9	11.2	10.9	12.5	11.7	11.6
Gage Stingray 874B[2]	–	7 hr	5 hr	1.5	–	6.6	10.6	–	7.2	8.8
Turco 6813	9 hr	3.5 hr	4 hr	2.1	2.7	10.6	9.6	11.1	10.1	10.5
Turco 6813-E	6 hr	5 hr	2.5 hr	2.7	2.8	9.5	9.4	9.6	9.1	9.5
Turco 6840-S	8 hr	4.5 hr	5 hr	2.2	2.2	11.1	11.8	10.8	12.4	12.2

Note: 1. Cee-Bee R-256 is a methylene chloride product being used as the alkaline/neutral baseline.
2. Gage Stingray 874B entered the study during Sequence 2; therefore Sequence 1 data do not exist for this product.

Table 3.2.1-4. Average Test Data for Acid Strippers (To Date)

Chemical Product	Average Dwell Time per Sequence			Average Surface Roughness (µin.)						
				Baseline	After Stripping			After Cleaning		
	Seq. 1	Seq. 2	Seq. 3	Measure-ment	Seq. 1	Seq. 2	Seq. 3	Seq. 1	Seq. 2	Seq. 3
Cee-Bee A-202	30 min	5 min	4 min	1.3	1.6	10.0	10.5	10.6	10.4	10.3
Cee-Bee E-1004B	6 hr	4 hr	3.5 hr	1.3	1.7	11.7	10.6	12.0	11.0	11.3
EZE 540	9 hr	5 hr	2.5 hr	1.2	1.5	9.9	10.4	11.0	10.3	10.3
PR-2002	9 hr	4 hr	3.5 hr	1.3	1.5	9.9	9.6	10.3	9.4	10.3
Turco 6776	6 hr	2.5 hr	2.5 hr	1.4	1.4	10.2	9.9	11.4	10.8	10.4

Note: Cee-Bee A-202 is a methylene chloride product being used as the acid baseline.

Dwell times ranged from 2.5 to 5 hours for the alkaline/neutral strippers, while the alkaline methylene chloride baseline stripped in 5 minutes. (See Table 3.2.1-5.) Dwell times ranged from 2.5 to 3.5 hours for the acid strippers, while the acid methylene chloride baseline stripped in 4 minutes. (See Table 3.2.1-6.)

Table 3.2.1-5. Test Parameters and Results for Alkaline/Neutral Strippers (Sequence 3)

Chemical Product	Panel Number	Clad or Non-Clad	Paint Thickness (mil)	Ave. Temperature/ Relative Humidity	Time to Strip	Average Surface Roughness (µin.)			
						Base-line	Cycle 1/2 After Cleaning	Cycle 2/3 After Cleaning	Cycle 3/4 After Cleaning
Cee Bee R-256[1]	I-2.20.1	non-clad	2.7	76/41%	5 min	1.4	14.4	12.2	17.3
Cee Bee R-256	I-2.20.2	non-clad	2.7	76/41%	5 min	1.3	14.2	12.2	10.6
Cee Bee R-256	I-7.10.1	clad	2.7	76/41%	5 min	1.2	8.8	9.3	6.3
Cee Bee R-256	I-7.20.1	clad	2.6	76/41%	5 min	1.1	10.1	10.8	10.4
Cee Bee R-256	I-7.20.2	clad	2.6	76/41%	5 min	1.0	15.2	13.8	13.2
Gage 874B[2]	I-1.6.2	non-clad	2.4	81/33%	5 hr	3.1	-	6.1	6.5
Gage 874B	I-2.15.3	non-clad	2.7	81/33%	5 hr	1.4	-	5.9	7.3
Gage 874B	I-7.1.1	clad	2.4	81/33%	5 hr	1.0	-	6.5	7.7
Gage 874B	I-7.1.2	clad	2.9	81/33%	5 hr	0.9	-	8.3	9.3
Gage 874B	I-7.6.2	clad	2.6	81/33%	5 hr	1.3	-	9.3	13.0
Turco 6813	I-1.2.1	non-clad	3.5	80/42%	4 hr	3.6	14.1	12.8	13.0
Turco 6813	I-1.2.2	non-clad	3.2	80/42%	4 hr	3.3	11.8	12.8	11.6
Turco 6813	I-7.2.1	clad	2.6	80/42%	4 hr	1.3	10.0	7.5	8.3
Turco 6813	I-7.2.2	clad	2.6	80/42%	4 hr	1.4	10.8	8.1	10.0
Turco 6813	I-7.9.2	clad	2.6	80/42%	4 hr	1.0	8.7	9.3	9.4
Turco 6813E	I-1.7.1	non-clad	2.5	75/49%	2.5 hr	4.0	12.2	12.2	12.4
Turco 6813E	I-1.7.2	non-clad	2.4	75/49%	2.5 hr	4.3	11.1	9.5	9.3
Turco 6813E	I-7.7.1	clad	2.6	75/49%	2.5 hr	2.7	9.5	8.3	9.6
Turco 6813E	I-7.7.2	clad	2.4	75/49%	2.5 hr	1.3	7.0	9.1	9.1
Turco 6813E	I-7.9.1	clad	2.5	75/49%	2.5 hr	1.0	8.2	6.7	7.3
Turco 6840S	I-1.5.1	non-clad	2.7	80/30%	5 hr	3.6	-	14.6	14.0
Turco 6840S	I-1.5.2	non-clad	2.5	80/30%	5 hr	3.6	13.2	14.4	12.6
Turco 6840S	I-7.5.1	clad	2.9	80/30%	5 hr	1.4	12.4	11.2	14.0
Turco 6840S	I-7.5.2	clad	2.9	80/30%	5 hr	1.3	9.4	10.2	10.6
Turco 6840S	I-7.8.2	clad	2.6	80/30%	5 hr	1.2	8.3	11.8	9.8

Note: 1. Cee-Bee R-256 is a methylene chloride product being used as the alkaline/neutral baseline.

2. Gage Stingray 874B entered the study during Sequence 2, and Sequence 1 data do not exist for this product. These test specimens also were not subjected to a phosphoric acid bath that produced significant etching and increased surface roughness values in the other test specimens during Sequence 1.

Table 3.2.1-6. Test Parameters and Results for Acid Strippers (Sequence 3)

Chemical Product	Panel Number	Clad or Non-Clad	Paint Thickness (mil)	Ave. Temperature/ Relative Humidity	Time to Strip	Average Surface Roughness (μin.)			
						Base-line	Cycle 1/2 After Cleaning	Cycle 2/3 After Cleaning	Cycle 3/4 After Cleaning
Cee Bee A-202	I-2.17.1	non-clad	2.7	76/41%	4 min	1.5	11.3	11.0	11.4
Cee Bee A-202	I-2.17.2	non-clad	2.6	76/41%	4 min	1.5	11.2	11.8	11.8
Cee Bee A-202	I-7.17.1	clad	2.4	76/41%	4 min	1.3	10.1	9.1	9.8
Cee Bee A-202	I-7.17.2	clad	3.1	76/41%	4 min	1.2	11.9	10.8	10.2
Cee Bee A-202	I-7.21.1	clad	2.9	76/41%	4 min	1.2	8.3	9.5	8.5
Cee Bee E-1004B	I-2.14.1	non-clad	2.9	81/28%	3.5 hr	1.5	11.8	11.0	13.0
Cee Bee E-1004B	I-2.14.2	non-clad	2.8	81/28%	3.5 hr	1.4	15.5	14.4	15.7
Cee Bee E-1004B	I-7.14.1	clad	2.3	81/28%	3.5 hr	1.1	13.7	11.0	12.2
Cee Bee E-1004B	I-7.14.2	clad	3.0	81/28%	3.5 hr	1.3	8.9	8.7	7.7
Cee Bee E-1004B	I-7.18.1	clad	2.8	81/28%	3.5 hr	1.0	10.2	9.8	8.1
EZE 540	I-2.11.1	non-clad	2.6	82/31%	2.5 hr	1.5	13.5	11.8	10.8
EZE 540	I-2.11.2	non-clad	2.6	82/31%	2.5 hr	1.3	13.8	12.6	11.8
EZE 540	I-7.11.1	clad	2.5	82/31%	2.5 hr	1.3	8.1	8.5	8.7
EZE 540	I-7.11.2	clad	2.5	82/31%	2.5 hr	1.0	9.3	7.7	8.5
EZE 540	I-7.13.1	clad	2.9	82/31%	2.5 hr	1.1	10.2	11.0	11.8
PR-2002	I-2.12.1	non-clad	3.2	82/31%	3.5 hr	1.9	10.2	9.5	11.0
PR-2002	I-2.12.2	non-clad	2.4	82/31%	3.5 hr	1.4	15.5	11.6	12.0
PR-2002	I-7.12.1	clad	2.6	82/31%	3.5 hr	0.9	6.6	7.5	6.9
PR-2002	I-7.12.2	clad	2.5	82/31%	3.5 hr	1.2	10.8	10.0	12.2
PR-2002	I-7.13.2	clad	3.0	82/31%	3.5 hr	1.2	8.5	8.3	9.6
Turco 6776	I-2.16.1	non-clad	2.4	77/37%	2.5 hr	1.5	13.9	13.2	11.0
Turco 6776	I-2.16.2	non-clad	2.5	77/37%	2.5 hr	1.8	14.5	12.6	12.8
Turco 6776	I-7.15.1	clad	2.2	77/37%	2.5 hr	1.2	10.6	9.5	9.3
Turco 6776	I-7.15.2	clad	3.1	77/37%	2.5 hr	1.2	8.9	10.4	10.2
Turco 6776	I-7.18.2	clad	2.5	77/37%	2.5 hr	1.1	9.0	8.5	8.5

Note: Cee-Bee A-202 is a methylene chloride product being used as the acid baseline.

Plans had called for both Stingray 874 and 894 to be added as alkaline/neutral strippers during Sequence 2. Gage Products Company, however, requested that these plans be canceled in favor of adding only Stingray 874B (a modified version of the Stingray 874 formulation tested during our site visit to the Raytheon facility in May 1996), which they consider a more promising product. Stingray 874B did not show signs of brightening or alodine removal during Sequence 2, unlike the product tested at Raytheon (as described in the *Fourth Progress Report*, Section 2.1). Since these test specimens entered the study during Sequence 2, they were not subjected to the phosphoric acid bath used during Sequence 1 that produced significant etching, which increased surface roughness values for the other test specimens.

Figures 3.2.1-1 through 3.2.1-3 show the setups for the chemical stripping tests. Figures 3.2.1-4 through 3.2.1-8 show comparisons of the debonding stages produced by the various stripping agents.

The MSFC points of contact are EH33/Robin Broad at (256) 544-7016 and EH33/Regina Moore at (256) 544-8456.

Figure 3.2.1-1. Test Setup of Methylene Chloride Panels (initial to intermediate debonding)

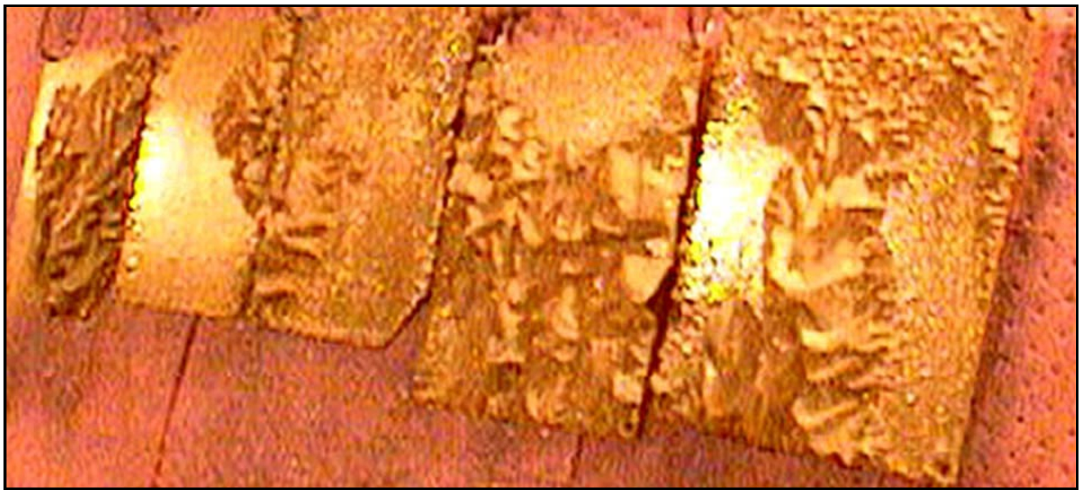


Figure 3.2.1-2. Test Setup of Alkaline/Neutral Panels (intermediate debonding)

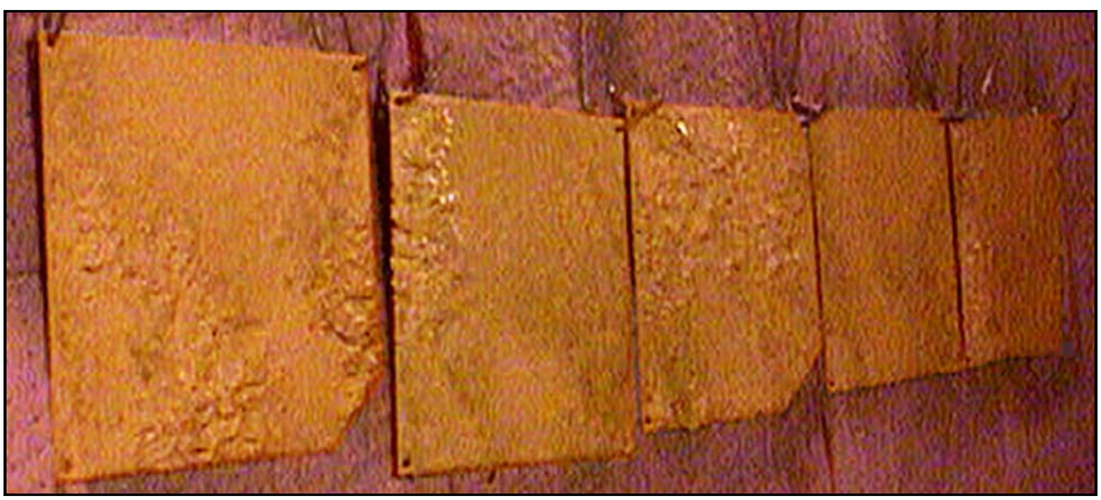


Figure 3.2.1-3. Test Setup of Acid Panels (intermediate debonding)

Figure 3.2.1-4. Intermediate Debonding on 0.064-in. Panel Brushed with Methylene Chloride Stripper

Figure 3.2.1-5. Full Debonding on 0.064-in. Panel Brushed with Methylene Chloride Stripper

Figure 3.2.1-6. Initial Debonding on Panel Sprayed with Non-Methylene Chloride Stripper

Figure 3.2.1-7. Intermediate Debonding on Panel Sprayed with Non-Methylene Chloride Stripper

Figure 3.2.1-8. Full Debonding on Panel Sprayed with Non-Methylene Chloride Stripper

3.2.2. CO_2 Blasting

No further testing will be conducted on the CO_2 blasting process, which was shown to be ineffective as a stand-alone paint removal process during Sequence 1.

3.2.3. FLASHJET® Coating Removal

During the third depainting sequence, this process was used to strip 24 control panels cut from non-clad 2024-T3 aluminum sheets that were 0.016 inch thick (14 specimens), 0.051 inch thick (4 specimens), and 0.064 inch thick (6 specimens). In July 1997, these panels were shipped to McDonnell Douglas Aerospace (MDA) in St. Louis, Missouri. (MDA became Boeing-St. Louis in August 1997 and, beginning with this report, will be referred to by that name.) By December 1997, all were stripped and returned to MSFC. (See Table 3.2.3-1 for test parameters.)

Table 3.2.3-1. Test Parameters for FLASHJET® Coating Removal (Sequence 3)

Coating Layer	**Input Voltage** (V)	**Repetition Rate** (flashes/sec)	**Stand-off Distance** (in.)	**Trans-lational Velocity** (in./sec)	**Stripping Passes**	**CO_2 Input Pressure to Nozzle** (psi)	**Media Flow Rate** (lb/hr)	**CO_2 Angle of Attack** (deg)
Topcoat	1900 to 2300	3 to 5	2 to 3	0.75 to 1.4	8	90 to 180	500 to 1000	21 to 29
Primer					4			

Note: Boeing-St. Louis considers specific FLASHJET® parameters to be proprietary information.

After stripping, the panels were visually inspected at MSFC. Table 3.2.3-2 shows average results, while Appendix A.2.3 gives detailed results.

Table 3.2.3-2. Average Results for FLASHJET® Coating Removal (Sequence 3)

Substrate			**Time to Strip[1]** (min:sec)	**Strip Rate** (in.^{2}/min)	**Surface Roughness After Stripping[2]** (µin.)	**Coatings Removed[3]**
Dimensions (in.)	**Thickness** (in.)	**Area Stripped** (in.^{2})				
22 by 22	0.016	484	6:55	70.0	20.5	–
	0.051	484	3:40	132.0	18.2	–
	0.064	484	4:48	100.8	17.2	–
12 by 12	0.064	144	1:34	91.9	16.6	–

Notes: 1. **Time to Strip** includes time used to make overlapping passes, which did not increase the amount of coating removed.

2. **Surface Roughness After Stripping** was measured even though coating remained on the substrate. This remaining coating was measured for its thickness and is reported in Tables 3.2.3-3 through 3.2.3-5. Figure 3.2.3-1 shows the location of measurements taken on the panels.

3. **Coatings Removed** are percentages based on pre-strip thickness data presented in Appendix 2.3 (primer: 0.6 to 0.9 mil; topcoat: 1.7 to 2.3 mil) and post-strip thickness data presented in Tables 3.2.3-3 through 3.2.3-5. Percentages of primer removed are shown in Table 3.2.3-6; virtually all topcoat was removed.

Table 3.2.3-3. Post-Strip Coating Thickness Readings for 0.016-in. Panels

Panel Number	**Substrate Thickness** (mil)	**Average Post-Strip Coating Thickness** (mil)	**Maximum Post-Strip Coating Thickness** (mil)	**Minimum Post-Strip Coating Thickness** (mil)	**Standard Deviation** (mil)
IV-14.1	16	0.26	0.32	0.11	0.07
IV-14.2	16	0.27	0.33	0.22	0.04
IV-14.3	16	0.31	0.41	0.15	0.09
IV-15.5	16	0.33	0.39	0.28	0.04
IV-15.6	16	0.32	0.39	0.21	0.06
IV-15.-7	16	0.37	0.46	0.24	0.07
IV-15.8	16	0.32	0.42	0.22	0.07
IV-15.9	16	0.34	0.48	0.20	0.08
IV-15.10	16	0.37	0.65	0.25	0.12
IV-15.11	16	0.35	0.46	0.24	0.08
IV-15.12	16	0.34	0.41	0.24	0.06
IV-16.13	16	0.34	0.40	0.28	0.04
IV-16.14	16	0.27	0.34	0.23	0.03
IV-16.15	16	0.30	0.35	0.21	0.05

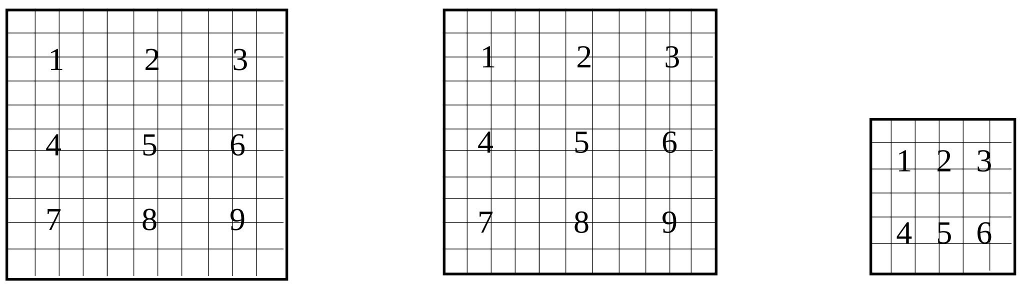
Table 3.2.3-4. Post-Strip Coating Thickness Readings for 0.051-in. Panels

Panel Number	**Substrate Thickness** (mil)	**Average Post-Strip Coating Thickness** (mil)	**Maximum Post-Strip Coating Thickness** (mil)	**Minimum Post-Strip Coating Thickness** (mil)	**Standard Deviation** (mil)
IV-9.5	51	0.19	0.23	0.17	0.02
IV-9.1	51	0.17	0.22	0.12	0.04
IV-9.2	51	0.20	0.25	0.16	0.03
IV-9.3	51	0.23	0.30	0.19	0.04

Table 3.2.3-5. Post-Strip Coating Thickness Readings for 0.064-in. Panels

Panel Number	**Substrate Thickness** (mil)	**Average Post-Strip Coating Thickness** (mil)	**Maximum Post-Strip Coating Thickness** (mil)	**Minimum Post-Strip Coating Thickness** (mil)	**Standard Deviation** (mil)
IV-I-1.10.2	64	0.32	0.36	0.27	0.03
IV-I-1.10.3	64	0.33	0.39	0.28	0.04
IV-I-1.9.2	64	0.32	0.35	0.30	0.02
IV-I-1.9.3	64	0.32	0.34	0.30	0.01
IV-I-1.9.4	64	0.30	0.33	0.27	0.02
IV-9.3	64	See Note.	See Note.	See Note.	See Note.

Note: Data were not recorded.



0.016-in. panels (22 in. by 22 in.) — 0.051-in. panels (22 in. by 22 in.) — 0.064-in. panels (12 in. by 12 in.)

Figure 3.2.3-1. Paint Thickness Reading Locations

During Sequence 2, as reported in the *Fifth Progress Report*, localized heating occurred in 11 of 15 of the 0.016-inch panels because only their outer edges were restrained by the test fixture. This method was inadequate to prevent a 22- by 22-inch sheet of thin-gauge material from being lifted toward the flashlamp by the vacuum system. For Sequence 3, Boeing-St. Louis designed, built, and used a vacuum hold-down fixture, which prevented lifting of the panels during stripping (Figure 3.2.3-2). The reader should note that such difficulties probably will not occur in actual service, where fabricated structures are unlikely to include an unsupported span of this length and gauge.

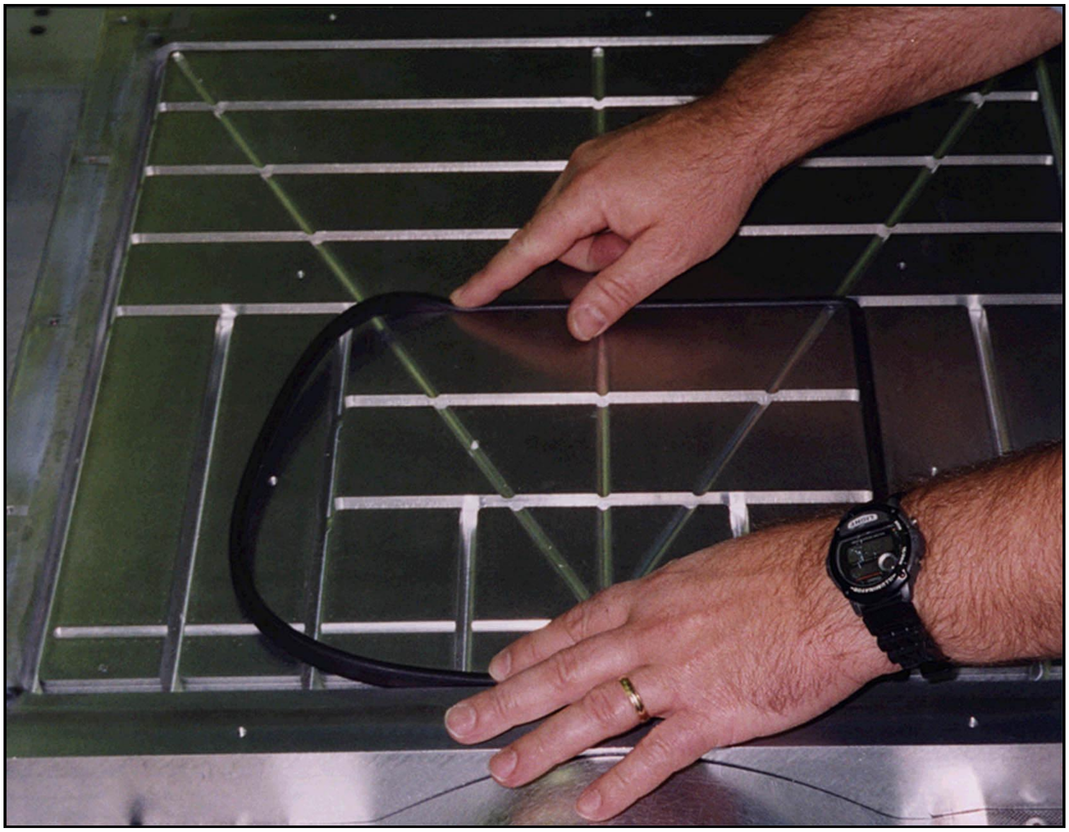


Figure 3.2.3-2. Boeing-St. Louis designed a vacuum plate to provide support to both the 22-in. by 22-in. panels and the 12-in. by 12-in. panels during FLASHJET® stripping. A technician installs a rubber gasket seal into the vacuum plate groove for 12-in. by 12-in. panel stripping.

After stripping, some control panels again contained residual primer that was not uniform over each panel's surface. Boeing-St. Louis' preferred approach is to leave approximately 0.5 mil or less of primer. Table 3.2.3-6 shows the approximate percentages of primer removed from the panels.

Table 3.2.3-6. Percentage Primer Removed

Panel Thickness (mil)	**Average Primer Thickness** (mil)	**Thickness Remaining** (mil)	**Percent Remaining** (%)	**Percent Removed** (%)
0.016	0.75	0.32	43	57
0.051	0.75	0.19	26	74
0.064	0.75	0.32	42	58

Note: Average Primer Thickness: (0.6 + 0.9)/2 = 0.75 mil

The non-uniform residual coating may be related to two factors: uneven paint thickness and uneven stripping, which occurs because the lamp's intensity is higher in the center of each stripping width and tapers off on each end. The FLASHJET® system can compensate somewhat by slightly overlapping each stripping pass and varying pass directions.

The MSFC point of contact is EH33/Steve Burlingame at (256) 544-8860.

3.2.4. CO_2 Laser Stripping

Panels to be CO_2 laser stripped during the third depainting sequence have been delivered to new TAC committee member, General Lasertronics Corporation of Santa Clara, California. Sequence 3 data for CO_2 laser stripping will be presented in the final report.

The MSFC point of contact is EH33/Steve Burlingame (256) 544-8860.

3.2.5. Plastic Media Blasting

During the third depainting sequence, this process was used to strip 29 control panels cut from non-clad 2024-T3 aluminum sheets that were 0.016 inch thick (12 specimens), 0.051 inch thick (3 specimens), and 0.064 inch thick (14 specimens). This process was also used to strip 10 control panels cut from clad 2024-T3 aluminum sheets that were 0.016 inch thick (5 specimens) and 0.032 inch thick (5 specimens). (See Table 3.2.5-1.)

Table 3.2.5-1. Test Parameters for Plastic Media Blasting (Sequence 3)

Substrate Thickness (in.)	**Pressure** (psi)	**Angle of Attack** (deg)	**Stand-off Distance** (in.)	**Media Flow Rate** (lb/hr)	**Mesh Size**
0.016	30	30	8 to 12	250 to 500	16/20 and 20/30 mix (20/80%)
0.032	35	30 to 45			
0.051	35	30			
0.064	40	30 to 45			

Note: Low pressures were used to blast these substrates to avoid bending caused by induced residual stresses. Early in the study, it became apparent that the 0.016-in. control panels could not be blasted at pressures higher than 30 psi without bending.

Testing was conducted at MSFC using a PMB unit from Titan Abrasive Systems (Model 6060SDCR). Type V plastic media were deployed, using a nozzle with an inside diameter of 0.5 inches at the throat. Strip rates were improved slightly by increasing the flow rate of the plastic media, as well as by combining some 16/20 mesh media with smaller 20/30 mesh media (at a ratio of 20 to 80%, respectively) to increase the aggressiveness of this process. Media effectiveness was noticeably reduced after ~10 strip sequences. Table 3.2.5-2 shows average results for the non-clad samples; Tables 3.2.5-3, 3.2.5-4, and 3.2.5-5 show average results for the clad samples; and Appendix A.2.5 gives detailed results.

Table 3.2.5-2. Average Results for Plastic Media Blasting of Non-Clad Samples (Sequence 3)

Substrate Thickness (in.)	**Stripped Area** (in.^{2})	**Time to Strip** (min:sec)	**Strip Rate** (in.^{2}/min)	**Surface Roughness After Stripping** (μin.)	**Coatings Removed**
0.016	484	17:50	27.08	20.9	100% topcoat and 80% primer
0.051	484	14:52	32.50	28.6	
0.064	144	5:21	26.99	14.2	

Table 3.2.5-3. Average Results for Plastic Media Blasting of Clad Samples (Sequence 1)

Substrate Thickness (in.)	**Stripped Area** (in.^{2})	**Time to Strip** (min:sec)	**Strip Rate** (in.^{2}/min)	**Surface Roughness After Stripping** (μin.)	**Coatings Removed**
0.016	484	23:09	20.9	37.5	100% topcoat and 80% primer
0.032	484	22:15	21.8	120.8	

Table 3.2.5-4. Average Results for Plastic Media Blasting of Clad Samples (Sequence 2)

Substrate Thickness (in.)	**Stripped Area** (in.^{2})	**Time to Strip** (min:sec)	**Strip Rate** (in.^{2}/min)	**Surface Roughness After Stripping** (μin.)	**Coatings Removed**
0.016	484	21:13	22.8	40.2	100% topcoat and 80% primer
0.032	484	19.10	25.3	94.0	

Table 3.2.5-5. Average Results for Plastic Media Blasting of Clad Samples (Sequence 3)

Substrate Thickness (in.)	**Stripped Area** (in.^{2})	**Time to Strip** (min:sec)	**Strip Rate** (in.^{2}/min)	**Surface Roughness After Stripping** (μin.)	**Coatings Removed**
0.016	484	17:31	27.63	See Note	100% topcoat and 80% primer
0.032	484	16:07	30.06	See Note	

Note: Because of an anomaly during processing, these data are not available.

Beginning in Sequence 3, our laboratory procedures were modified to adopt process parameters that are more representative of production stripping in the field. For Sequences 1 and 2, we used a nozzle with an inside diameter of 0.25 inches at the throat. For Sequences 3 and 4, we are using a nozzle with an inside diameter of 0.5 inches at the throat. (This change increased the stripping rate.) The 3-inch stand-off distance was increased to 8 to 12 inches during this cycle.

The MSFC point of contact is EH33/Johnnie Clark at (256) 544-2799.

3.2.6. Sodium Bicarbonate Wet Stripping

Data for the third depainting cycle for this process will be reported in the final report.

The MSFC point of contact is EH33/David Hoppe at (256) 544-8836.

3.2.7. WaterJet Blasting

Data for the third depainting cycle for this process will be reported in the final report.

The MSFC point of contact is EH33/David Hoppe at (256) 544-8836.

3.2.8. ENVIROSTRIP® Wheat Starch Blasting

During the third depainting sequence, this process was used to strip 30 control panels cut from non-clad 2024-T3 aluminum sheets that were 0.016 inch thick (19 specimens), 0.051 inch thick (5 specimens), and 0.064 inch thick (6 specimens). In late July 1997, they were shipped to the ENVIROSTRIP® Test Center (jointly operated by ADM/Ogilvie and CAE Electronics, Ltd.) in Montreal, Quebec, Canada. By early September 1997, all panels had been stripped and returned to MSFC.

The panels were depainted using ENVIROSTRIP® wheat starch media in a typical production mix, determined by removing various coating systems at standard operating parameters (20 to 40 psi, 8 to 18 lb). New media (12 to 30) were continuously added to the mix at a rate of 10 to 15% per cycle. The mix had a broad particle size range (12 to 120), the majority being between 20 and 100.

During Sequence 3, the manual system produced strip rates similar to those reported for Sequence 2 for the 0.051-inch and 0.64-inch thick panels; the manual strip rates for the six 0.016-inch thick panels fell between those of the first and second sequences (data appearing in the *Fifth Progress Report*). The semi-automatic system also produced strip rates similar to those reported for Sequence 2.

The MSFC point of contact is EH33/Steve Burlingame at (256) 544-8860.

3.2.8.1. Manual

Manual blasting was performed on 11 control panels cut from non-clad 2024-T3 aluminum sheets that were 0.016 inch thick (6 specimens), 0.051 inch thick (2 specimens), and 0.064 inch thick (3 specimens). (See Table 3.2.8.1-1.)

Table 3.2.8.1-1. Test Parameters for Manual ENVIROSTRIP® Wheat Starch Blasting (Sequence 3)

Substrate Thickness (in.)	Pressure (psi)	Media Flow Rate (lb/min)	Mesh Size	Projection Angle (deg)	Stand-off Distance (in.)	Stripping Width (in.)
0.016	20	18	12 to 120	30 to 60	4 to 8	0.75
0.051	30	12				
0.064	30	12				

The operator used a standard 0.5-inch double venturi nozzle. No statistically significant changes were seen in surface roughness values, which remained well within acceptable levels. Table 3.2.8.1-2 shows average results, while Appendix A.2.8 gives detailed results.

Table 3.2.8.1-2. Average Results for Manual ENVIROSTRIP® Wheat Starch Blasting (Sequence 3)

Substrate Thickness (in.)	Time to Strip (min:sec)	Strip Rate ($in.^2/min$)	Surface Roughness After Stripping (µin.)	Coatings Removed
0.016	3:03	71.0	18.7	100% topcoat and 99% primer
0.051	2:04	105.3	17.0	
0.064	1:58	110.0	15.2	

3.2.8.2. Semi-Automatic

Semi-automatic blasting was performed on 19 panels cut from non-clad 2024-T3 aluminum sheets that were 0.016 inch thick (13 specimens), 0.051 inch thick (3 specimens), and 0.064 inch thick (3 specimens). (See Table 3.2.8.2-1.)

Table 3.2.8.2-1. Test Parameters for Semi-Automatic ENVIROSTRIP® Wheat Starch Blasting (Sequence 3)

Substrate Thickness (in.)	Translational Velocity (in./sec)	Pressure (psi)	Media Flow Rate (lb/min)	Mesh Size	Projection Angle (deg)	Stand-off Distance (in.)	Stripping Width (in.)
0.016	1.2	20	18	12 to 120	45	3	4.25
0.051	2.1	40	12				
0.064	2.1	40	12				

The test system included a computer-controlled four-axis gantry-style robotic system designed by CAE, with a CAE T-7 flat nozzle**.** No statistically significant changes were seen in surface roughness values, which remained well within acceptable levels. Table 3.2.8.2-2 shows average results, while Appendix A.2.8 gives detailed results.

Table 3.2.8.2-2. Average Results for Semi-Automatic ENVIROSTRIP® Wheat Starch Blasting (Sequence 3)

Substrate Thickness (in.)	Time to Strip	Strip Rate (in.^{2}/min)	Surface Roughness After Stripping (μin.)	Coatings Removed
0.016	44	293.3	19.9	100% topcoat and 99% primer
0.051	24.2	535.5	15.1	
0.064	24.2	535.5	15.7	

3.3. Surface Roughness

These measurements allow determination of any changes to the roughness of the substrate surface that may have been caused by the depainting processes under study. SAE MA4872 (draft 4) requires that all surface roughness measurements remain <125 microinches after a minimum of 5 depainting cycles. Surface roughness measurements that exceed this requirement may indicate that the substrate's structural integrity has been compromised.

The test specimens were measured using a Giddings and Lewis profilometer and a Hommelwerke T500 profilometer (operator choice). Both give values of R_a, the arithmetic mean roughness value, and both were checked with the same roughness standard before taking measurements.

Surface roughness measurements were taken at a number of locations on each substrate, the number varying according to test specimen size. The original baseline measurements were made after the test specimens were cut, cleaned, and iridited (but before they were coated and aged for the first stripping sequence). During each sequence, each test specimen was measured after stripping and after cleaning in preparation for coating and aging during the next sequence. (See Tables 3.3-1, 3.3-2, and 3.3-3.)

The most significant effect in surface roughness to date has been a one-time attempt to use a phosphoric acid bath to remove alodine and residual coatings from the control panels after stripping during Sequence 1. As a result, surface roughness values unexpectedly increased during post-cleaning measurements for Sequence 1, which led to a decision to remove the phosphoric acid bath from the cleaning procedure. (See Section 3.1.1, *Fifth Progress Report*.)

Post-stripping surface roughness values for Sequences 2 and 3 for the chemical stripping, FLASHJET®, and ENVIROSTRIP® wheat starch processes showed little change from post-cleaning surface roughness values for Sequence 1. For the plastic media blasting process, the surface roughness measurements for all panels increased dramatically from the baseline to the first post-stripping measurements. The first post-stripping surface roughness measurements for two of these panels surpassed the 125-microinch limit, but as they were cleaned, their surface roughness dropped below this limit. The Sequence 1 post-cleaning surface roughness measurements for all the PMB clad panels decreased. With further processing during Sequence 2, the surface roughness measurements continued to decrease. Possible reasons for this include (1) the decrease in remnant primer after stripping as our stripping skills improved, (2) the fact that it is not possible to take each set of measurements at precisely the same points on a substrate, and (3) the possibility that, during each depainting cycle, some clad material may be lost, so that the measurements would have been made on the smoother, bare material.

The MSFC point of contact is EH12/Miria Finckenor at (256) 544-9244.

Table 3.3-1. Average Surface Roughness Measurements (μin.) Through Sequence 2

Depainting Process	Baseline Measurements	Sequence 1[1]		Sequence 2[2]		Increase in Surface Roughness (Baseline to) Sequence 2	
		After Stripping	After Cleaning	After Stripping	After Cleaning	After Stripping	After Cleaning
Chemical	1.6[3]	1.8[4]	11.0	10.1	10.2	+8.5	+8.6
FLASHJET®	1.9	27.0	15.7	16.8	14.7	+14.9	+12.8
CO_2 Laser	2.3	13.2	13.4	13.3	12.4	+11.0	+10.1
PMB	2.5	14.2	33.7	20.9	18.3	+18.4	+15.8
Sodium Bicarbonate	1.8	34.2	23.1	24.4	23.0	+22.6	+21.2
WaterJet	1.9	7.3	24.5	25.3	26.1	+23.4	+24.2
ENVIROSTRIP® Wheat Starch	1.3	2.7	25.4	18.2	19.4	+16.9	+18.1

Notes:

1. During Sequence 1, the cleaning procedure included a phosphoric acid bath that etched the control panels, greatly increasing surface roughness values. After Sequence 1, the phosphoric acid bath was eliminated from the cleaning process.

2. In this table, some processes appear to have produced lower surface roughness values during Sequence 2 than during Sequence 1. This phenomenon, however, is a result of the fact that approximately nine separate measurements are averaged to arrive at each surface roughness value shown. Some variability also results from the fact that each set of measurements must be taken at random locations on the control panel, since it is not possible to make each set of measurements at the same points with any precision.

3. In the *Fourth* and *Fifth Progress Reports*, the average baseline measurement for chemical stripping (1.2) was the average of all initial panels (102) designated for chemical stripping. As the study has progressed, the number of chemical stripping panels has stabilized at 50; therefore, beginning with this report, the baseline measurement for chemical stripping (1.6) is the average of these 50 panels alone.

4. As reported in the *Fifth Progress Report*, only those chemically stripped panels that were measured for ESCA surface analysis after stripping were measured for surface roughness after stripping. This figure (1.8) is the average for the 25 panels that remain in the chemical stripping process and that were measured for surface roughness after stripping. For the remaining sequences, average after-stripping surface roughness data for chemical stripping include all 50 panels.

Table 3.3-2. Sequence 3[1] Average Surface Roughness Measurements (μin.)

Depainting Process	Baseline Measurements	Sequence 3		Increase in Surface Roughness (Baseline to Sequence 3)	
		After Stripping	After Cleaning	After Stripping	After Cleaning
Chemical	1.6	10.3	10.5	+8.7	+8.9
FLASHJET®	1.9	19.2	15.2	+17.3	+13.3
CO_2 Laser[2]	2.3	—	—	—	—
PMB	2.5	18.5	16.2	+16.3	+13.7
BOSS[2]	1.8	—	—	—	—
WaterJet[2]	1.9	—	—	—	—
ENVIROSTRIP® Wheat Starch	1.3	18.1	16.8	+16.8	+15.5

Notes: 1. A complete list of surface roughness measurements is given in Appendix A.3.

2. Sequence 3 surface roughness data for CO_2 laser stripping, BOSS, and WaterJet will be presented in the next progress report.

Table 3.3-3. Sequences 1 and 2 Average Surface Roughness Measurements (μin.) for PMB Clad Panels

Baseline Measurements	Sequence 1		Sequence 2		Increase in Surface Roughness (Baseline to Sequence 1)		Increase in Surface Roughness (Baseline to Sequence 2)	
	After Stripping	After Cleaning	After Stripping	After Cleaning	After Stripping	After Cleaning	After Stripping	After Cleaning
1.6	78.1	74.4	67.1	43.6	76.5	72.8	65.5	42

Note: A complete list of PMB surface roughness measurements is given in Appendix A.3.

4.0 METALLURGICAL EVALUATIONS

Several metallurgical evaluations are now being made of eight environmentally advantaged chemicals, including alkaline/neutral strippers (Gage Stingray 874B and Turco 6813, 6813-E, and 6840-S) and acid strippers (Cee-Bee E-1004B, EZE 540, PR-2002, and Turco 6776), as well as this study's two alkaline/neutral and acid methylene chloride baselines (Cee-Bee R-256 and Cee-Bee A-202, respectively). The following tasks are being performed to determine the corrosion and hydrogen embrittlement potentials that these chemicals may hold for clad and non-clad 2024-T3 aluminum substrates.

- American Society for Testing & Materials (ASTM) F483-90, "Standard Test Method for Total Immersion Corrosion Test for Aircraft Maintenance Chemicals," is being conducted to determine the corrosiveness of these chemicals on aircraft metals with time under conditions of total immersion by a combination of weight change measurements and visual qualitative determination of change. Since many aircraft maintenance chemicals are used on components and structures that would be affected adversely by excessive dimensional change, this test method screens the chemicals to ensure compliance with specified weight change criteria.

- ASTM F1110-90, "Standard Test Method for Sandwich Corrosion Test," is being conducted to evaluate the corrosivity of these chemicals on aluminum alloys commonly used for aircraft structures. This test method is used in the qualification and approval of compounds employed in aircraft maintenance operations.

- ASTM F519-93, "Standard Test Method for Mechanical Hydrogen Embrittlement Testing of Plating Processes and Aircraft Maintenance Chemicals," is being conducted to evaluate any hydrogen embrittlement potential that may arise as various sources of hydrogen (*e.g.*, plating processes, fluids, cleaning treatments, maintenance chemicals, gaseous environments that may contact the surface of steels) interact with substrates stripped with these chemicals.

Mechanical testing is being conducted per SAE MA4872, "Paint Stripping of Commercial Aircraft - Evaluation of Materials and Processes," to determine effects on fatigue life (Type II) for all processes, as well as crack detectability for the four media blast processes: sodium bicarbonate wet stripping, PMB, WaterJet, and ENVIROSTRIP® wheat starch.

MSFC points of contact are EH22/Pete Belcher at (256) 544-3378, EH22/Pablo Torres at (256) 544-2616, EH23/Dr. Preston McGill at (256) 544-2604, and EH23/Hansel Gill at (256) 544-9027.

4.1. Total Immersion Corrosion Testing (ASTM F483-90)

Over 60 test coupons were fabricated with the dimensions of 2 inches by 1 inch by 0.064 inch (50.8 mm by 25.4 mm by 1.6 mm) from clad and non-clad 2024-T3 aluminum alloy. The non-clad material was anodized per MIL-A-8625C, Type 1 for chromic acid. Test results (as reported in the *Fifth Progress Report*) are represented here in Tables 4.1-1 through 4.1-6. Note that all chemicals were tested in the as-received condition. A detailed outline of the test procedure is presented in the *Fifth Progress Report*, Section 3.3.3.1.

An assessment of these data suggests that almost no weight loss was exhibited over the test period by coupons treated with alkaline/neutral strippers. Significantly higher weight loss was seen for coupons treated with acid strippers. The highest long-term removal rates were noted with Turco 6776, followed by EZE 540.

- For clad substrates, all tested chemicals resulted in acceptable weight loss rates per SAE MA4872. Cee-Bee A-202 (the acid methylene chloride baseline) and PR-2002 produced etching, pitting, and localized attack on clad coupons.
- For non-clad substrates, almost all chemicals produced acceptable weight loss rates per SAE MA4872. Turco 6776, EZE 540, and Cee-Bee A-202, however, produced weight loss rates in excess of the maximum rate specified (0.2 $mg/cm^2/24$ hr). EZE 540 and Cee-Bee A-202 produced etching, pitting, and localized attack on non-clad coupons.

Table 4.1-1. Average Weight Loss Rates for Clad and Non-Clad 2024-T3 Test Coupons during Total Immersion Corrosion Testing

Chemical Tested	Non-Clad 2024-T3		Clad 2024-T3	
	Exposed for 24 hr	Exposed for 168 hr	Exposed for 24 hr	Exposed for 168 hr
Turco 6813 (Alkaline)	0.0035	-0.0005	0.0000	-0.0025
Turco 6813-E (Alkaline)	0.0071	-0.0015	0.0000	-0.0020
Turco 6840-S (Alkaline)	0.0000	-0.0010	-0.0071	-0.0020
Stingray 874B (Neutral)	0.0000	-0.0005	0.0000	-0.0010
Cee-Bee R-256 (Alkaline baseline)	0.0000	0.0015	0.0000	-0.0015
Turco 6776 (Acid)	0.3121	0.4189	0.2092	0.3440
EZE 540 (Acid)	0.2943	0.2771	0.2624	0.2036
PR-2002 (Acid)	0.0319	0.0709	0.0000	0.1054
Cee-Bee E-1004B (Acid)	0.1986	0.1717	0.1773	0.1327
Cee-Bee A-202 (Acid baseline)	0.2979	0.2594	0.1950	0.1753

Note: These measurements represent average weight loss divided by total coupon area (28.2 cm^2) expressed as loss in milligrams per square centimeter per 24 hours. Negative numbers indicate weight gains, possibly caused by very slight variations in measurement and/or the presence of remnant corrosion deposits, since these test coupons were not electrolytically cleaned.

Table 4.1-2. Complete Data for Clad and Non-Clad 2024-T3 Test Coupons during Total Immersion Corrosion Testing

Chemical Tested	Non-Clad 2024-T3			Clad 2024-T3		
	Coupon Number	Weight Loss (mg)		Coupon Number	Weight Loss (mg)	
		After 24 hr	After 168 hr		After 24 hr	After 168 hr
Turco 6813 (Alkaline)	1	0.1	-0.2	49	0.0	-0.5
	2	0.1	0.0	50	0.0	-0.4
	3	0.1	0.0	51	0.0	-0.7
	Average	0.1	-0.1	Average	0.0	-0.5
Turco 6813-E (Alkaline)	4	0.3	-0.2	52	0.0	-0.3
	5	0.2	-0.2	53	0.0	-0.4
	6	0.0	-0.5	54	0.0	-0.4
	Average	0.2	-0.3	Average	0.0	-0.4
Turco 6840-S (Alkaline)	7	0.0	-0.6	55	0.0	-0.2
	8	0.0	0.0	56	-0.5	-0.8
	9	0.0	-0.1	57	-0.1	-0.3
	Average	0.0	-0.2	Average	-0.2	-0.4
Stingray 874B (Neutral)	10	0.0	0.0	58	0.0	-0.3
	11	0.0	-0.2	59	0.0	-0.1
	12	0.1	0.0	60	0.1	-0.2
	Average	0.0	-0.1	Average	0.0	-0.2
Cee-Bee R-256 (Alkaline baseline)	13	0.0	-0.2	61	-0.1	-0.3
	14	0.0	-0.3	62	0.0	-0.3
	15	0.0	-0.3	63	0.0	-0.4
	Average	0.0	-0.3	Average	0.0	-0.3
Turco 6776 (Acid)	16	10.6	90.7	64	4.7	58.8
	17	7.7	82.1	65	5.5	62.1
	18	8.2	75.4	66	7.4	82.8
	Average	8.8	82.7	Average	5.9	67.9
EZE 540 (Acid)	19	11.3	61.1	67	6.4	35.2
	20	7.0	56.6	68	10.5	43.8
	21	6.5	46.4	69	5.4	41.6
	Average	8.3	54.7	Average	7.4	40.2
PR-2002 (Acid)	22	1.2	12.8	70	- 0.1	19.2
	23	1.0	9.4	71	- 0.2	25.0
	24	0.4	19.8	72	0.4	18.3
	Average	0.9	14.0	Average	0.0	20.8
Cee-Bee E-1004B (Acid)	25	4.5	28.5	73	6.3	29.4
	26	5.2	34.1	74	4.0	24.5
	27	7.1	39.1	75	4.7	24.7
	Average	5.6	33.9	Average	5.0	26.2
Cee-Bee A-202 (Acid baseline)	28	8.2	52.3	76	5.1	33.6
	29	8.5	50.9	77	6.1	35.2
	30	8.5	50.3	78	5.4	35.1
	Average	8.4	51.2	Average	5.5	34.6

Note: Negative numbers indicate weight gains, possibly the result of very slight variations in measurement and/or the presence of remnant corrosion deposits, since these test coupons were not electrolytically cleaned.

Table 4.1-3. Visible Changes in Non-Clad 2024-T3 Test Coupons after Total Immersion Corrosion Testing (24-hr Exposure)

Chemical Tested	Coupon Number	Discoloration or Dulling	Etching	Accretions Presence and Relative Amounts	Pitting	Selective or Localized Attack
Turco 6813 (Alkaline)	1	yes	no	no	no	no
	2					
	3					
Turco 6813-E (Alkaline)	4	yes	no	no	no	no
	5					
	6					
Turco 6840-S (Alkaline)	7	no	no	no	no	no
	8	some				
	9	no				
Stingray 874B (Neutral)	10	some	no	no	no	no
	11	some				
	12	no				
Cee-Bee R-256 (Alkaline baseline)	13	no	no	no	no	no
	14	one spot				
	15	no				
Turco 6776 (Acid)	16	yes	yes	no	no	no
	17					
	18					
EZE 540 (Acid)	19	a little	yes	no	no	no
	20					
	21					
PR-2002 (Acid)	22	yes (spots)	some	no	no	yes
	23		some			
	24		no			
Cee-Bee E-1004B (Acid)	25	yes (yellow spots)	yes	no	no	no
	26					
	27					
Cee-Bee A-202 (Acid baseline)	28	yes (brown spots)	yes	no	no	no
	29					
	30					

Note: A bleached appearance was noted on all coupons tested with Cee-Bee A-202.

Table 4.1-4. Visible Changes in Clad 2024-T3 Test Coupons after Total Immersion Corrosion Testing (24-hr Exposure)

Chemical Tested	Coupon Number	Discoloration or Dulling	Etching	Accretions Presence and Relative Amounts	Pitting	Selective or Localized Attack
Turco 6813 (Alkaline)	49 50 51	no	no	no	no	no
Turco 6813-E (Alkaline)	52 53 54	no	no	no	no	no
Turco 6840-S (Alkaline)	55 56 57	no	no	no	no	no
Stingray 874B (Neutral)	58 59 60	no	no	no	no	no
Cee-Bee R-256 (Alkaline baseline)	61 62 63	no	no	no	no	no
Turco 6776 (Acid)	64 65 66	yes (coupons whitened)	yes	no	no	no
EZE 540 (Acid)	67 68 69	yes (coupons whitened)	yes	no	no	no
PR-2002 (Acid)	70 71 72	yes (many spots)	no	no	no	no
Cee-Bee E-1004B (Acid)	73 74 75	yes (coupons whitened)	yes	no	no	no
Cee-Bee A-202 (Acid baseline)	76 77 78	yes (coupons whitened)	yes	no	no	no

Note: A bleached appearance was noted on all coupons tested with acid strippers, as a result of etching.

Table 4.1-5. Visible Changes in Non-Clad 2024-T3 Test Coupons after Total Immersion Corrosion Testing (168-hr Exposure)

Chemical Tested	Coupon Number	Discoloration or Dulling	Etching	Accretions Presence and Relative Amounts	Pitting	Selective or Localized Attack
Turco 6813 (Alkaline)	1	yes	no	no	no	no
	2					
	3					
Turco 6813-E (Alkaline)	4	yes	no	no	no	no
	5					
	6					
Turco 6840-S (Alkaline)	7	no	no	no	no	no
	8	small spots				
	9	no				
Stingray 874B (Neutral)	10	very little	no	no	no	no
	11	a little				
	12	no				
Cee-Bee R-256 (Alkaline baseline)	13	very little	no	no	no	no
	14	very little				
	15	no				
Turco 6776 (Acid)	16	yes (coupons whitened)	yes	no	no	no
	17					
	18					
EZE 540 (Acid)	19[1]	yes	yes	no	some	yes
	20					
	21					
PR-2002[2] (Acid)	22	yes (many spots)	yes	no	yes	yes
	23					
	24					
Cee-Bee E-1004B (Acid)	25	yes	yes	no	some	yes
	26					
	27					
Cee-Bee A-202[3] (Acid baseline)	28	yes	yes	no	yes	yes
	29					
	30					

Notes:

1. Discoloration or dulling of the coupons was typically accompanied by spots on the surface, which might be attributed to corrosion deposits. The largest spots were found on coupons 19 through 27.

2. PR-2002 produced a very deteriorated appearance on coupons 22, 23, and 24.

3. Cee-Bee A-202 (a methylene chloride stripper being used as the acid baseline) produced more pitting on non-clad coupons than any other chemical product. Extensive pitting was seen on coupon 28.

Table 4.1-6. Visible Changes in Clad 2024-T3 Test Coupons after Total Immersion Corrosion Testing (168-hr Exposure)

Chemical Tested	Coupon Number	Discoloration or Dulling	Etching	Accretions Presence and Relative Amounts	Pitting	Selective or Localized Attack
Turco 6813 (Alkaline)	49	some	no	no	no	no
	50	very little				
	51	some				
Turco 6813-E (Alkaline)	52	some	no	no	no	no
	53					
	54					
Turco 6840-S (Alkaline)	55	very little	no	no	no	no
	56					
	57					
Stingray 874B (Neutral)	58	no	no	no	no	no
	59					
	60					
Cee-Bee R-256 (Alkaline baseline)	61	some	no	no	no	no
	62	very little				
	63	very little				
Turco 6776 (Acid)	64	yes (coupons whitened)	yes	no	no	no
	65					
	66					
EZE 540 (Acid)	67	yes	yes	no	no	no
	68					
	69					
PR-2002 (Acid)	70[1]	yes	yes	no	yes	yes
	71	some			no	no
	72[1,2]	yes			yes	yes
Cee-Bee E-1004B (Acid)	73	yes	yes	no	almost none	no
	74					
	75					
Cee-Bee A-202 (Acid baseline)	76	yes	yes	no	yes	yes
	77					
	78					

Notes: 1. Coupons 70 and 72 had large spots on their surfaces, which might be attributed to corrosion deposits.

2. Coupon 72 had a very deteriorated appearance.

4.2. Sandwich Corrosion Testing (ASTM F1110-90)

Test coupons were fabricated with the dimensions of 2 inches by 4 inches by 0.064 inch (50.8 mm by 100.2 mm by 1.6 mm) using clad and non-clad 2024-T3 aluminum alloy. Non-clad material was anodized per MIL-A-8625C, Type 1 for chromic acid. Four test coupon sandwiches were tested per chemical per alloy, each comprised of two individual test coupons sandwiched together in pairs of the same alloy and surface treatment. Four coupon sandwiches were tested with reagent deionized water (per ASTM D1193, Type IV) as controls for comparative purposes. All panels were cleaned, first with acetone, then with ethyl alcohol.

Both clad and non-clad sandwich pairs were used to test all chemicals, which were mixed thoroughly to ensure uniformity before being applied to the test coupons. In each case, a piece of glass fiber filter paper was fit over one coupon of the sandwiched pair. First, the paper was saturated with the as-received test solution. Then, the wet paper was covered with the second coupon of the sandwich pair. (Reagent water was used as a test solution for the control group per ASTM F1110-90.)

This test had a duration of 168 hours. For 4 days, the sandwich pairs were exposed for 8 hours in an air oven maintained at 100 °F (37.7 °C). Immediately afterward, they were moved to a humidity cabinet maintained at 100 ±2 °F (37.7 ±1 °C) and a relative humidity of 95 to 100%, where they were exposed for 16 hours. On the fifth day, the sandwich pairs were again exposed for 8 hours in the air oven at 100 °F (37.7 °C) and then moved to the humidity cabinet [100 ±2 °F (37.7 ±1 °C) and relative humidity 95 to 100%], where they were exposed for the last 64 hours. Each set was exposed individually (not stacked) in a horizontal position. (See Table 4.2-1.)

Table 4.2-1. Exposure Schedule for Sandwich Corrosion Testing

Step	Exposure Time (± 0.5 hr)	Temperature	Relative Humidity
1	8 hr	100 °F (37.7 °C)	Ambient
2	16 hr	100 °F (37.7 °C)	95 to 100%
3	8 hr	100 °F (37.7 °C)	Ambient
4	16 hr	100 °F (37.7 °C)	95 to 100%
5	8 hr	100 °F (37.7 °C)	Ambient
6	16 hr	100 °F (37.7 °C)	95 to 100%
7	8 hr	100 °F (37.7 °C)	Ambient
8	16 hr	100 °F (37.7 °C)	95 to 100%
9	8 hr	100 °F (37.7 °C)	Ambient
10	64 hr	100 °F (37.7 °C)	95 to 100%

After exposure, the panels were cleaned with warm tap water and lightly scrubbed with a soft nonmetallic bristle brush. Each specimen set was then dried and examined under 10x magnification and rated according to scales provided in ASTM F1110-90. (See Table 4.2-2.)

Table 4.2-2. Rating Scale for Sandwich Corrosion Testing

Rating	Condition
0	No visible corrosion
1	Very slight corrosion or discoloration (up to 5% of the surface area corroded)
2	Slight corrosion (5 to 10% of the surface area corroded)
3	Moderate corrosion (10 to 25% of the surface area corroded)
4	Extensive corrosion or any pitting (25% or more of the surface area corroded)

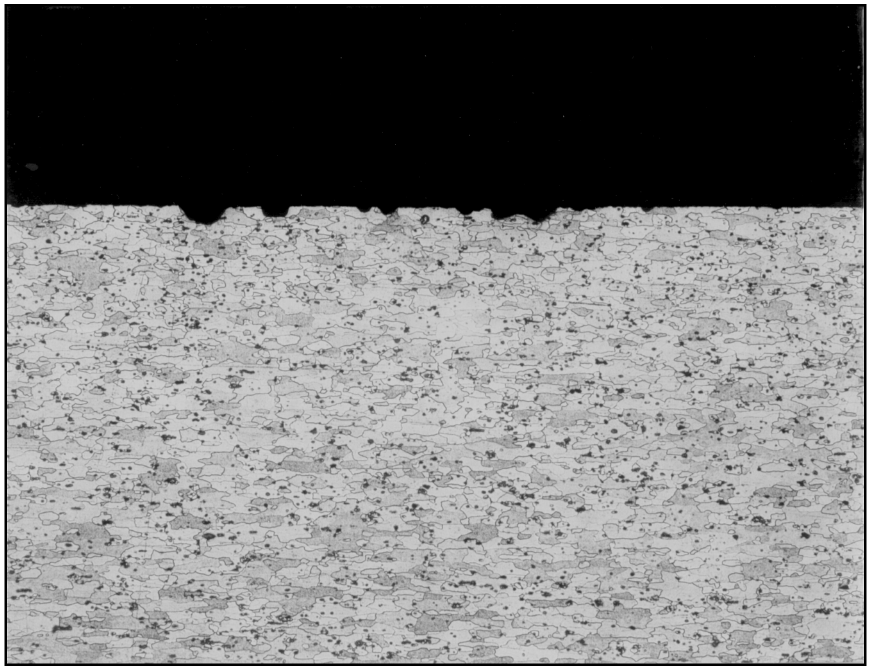
Corrosion ratings were then compared for coupons tested with chemicals versus the control group, *i.e.*, coupons tested with reagent water. These comparisons only considered the surfaces that were under the filter paper, and any corrosion at the edges was disregarded. (See Table 4.2-3.) Any corrosion in excess of that shown by the control group is considered cause for rejection, according to ASTM F1110-90. Test data from the sandwich corrosion testing were presented in the *Fifth Progress Report* and are represented here in Table 4.2-3.

On clad material, reagent water appears to have produced more severe corrosion or discoloration than did the chemicals. Cross sections of selected samples are presented in Figures 4.2.-1, 4.2.-2, and 4.2-3. On non-clad material, all acid strippers produced more severe corrosion than did reagent water.

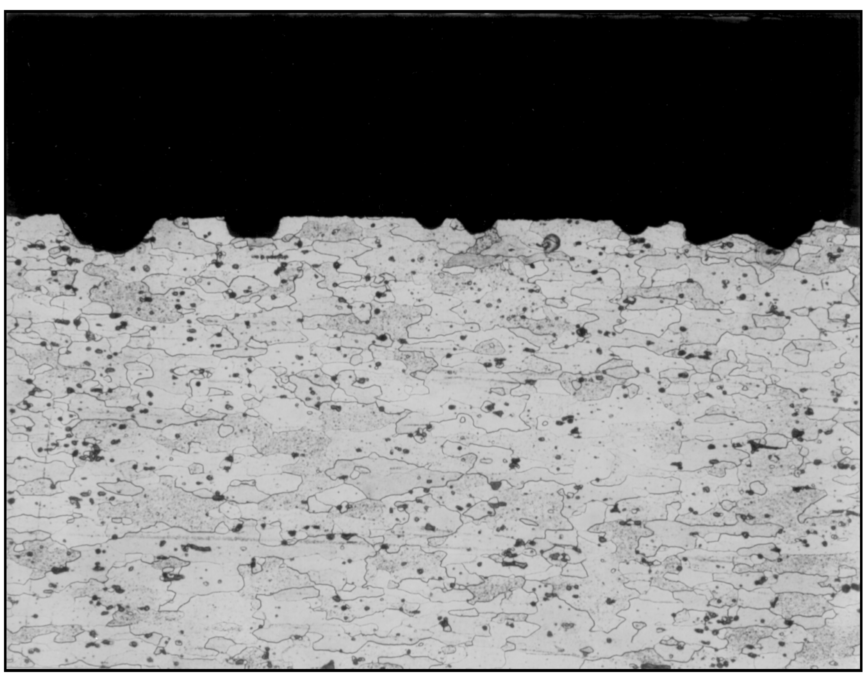
Table 4.2-3. Sandwich Corrosion Test Results[1]

Chemical Tested	Non-clad 2024-T3		Clad 2024-T3	
	Sandwich Number	Rating	Sandwich Number	Rating
Deionized Water[2,3] (Control group per ASTM D1193, Type IV)	1	3	121	3
	3	3	123	3
	5	3	125	3
	7	3	127	3
Turco 6813 (Alkaline)	9	1	129	3
	11	2	131	3
	13	2	133	3
	15	3	135	3
Turco 6813-E (Alkaline)	17	2	137	2
	19	2	139	3
	21	2	141	2
	23	2	143	3
Turco 6840-S (Alkaline)	25	3	145	2
	27	3	147	3
	29	2	149	2
	31	2	151	3
Stingray 874B (Neutral)	33	3	153	3
	35	3	155	3
	37	3	157	3
	39	3	159	3
Cee-Bee R-256 (Alkaline/neutral baseline)	41	2	161	1
	43	3	163	2
	45	2	165	2
	47	3	167	1
Turco 6776 (Acid)	49	4	169	3
	51	4	171	3
	53	4	173	3
	55	4	175	3
EZE 540 (Acid)	57	4	177	3
	59	4	179	4
	61	4	181	3
	63	4	183	3
PR-2002 (Acid)	65	4	185	3
	67	4	187	3
	69	4	189	3
	71	4	191	3
Cee-Bee E-1004B (Acid)	73	4	193	3
	75	4	195	2
	77	4	197	3
	79	4	199	2
Cee-Bee A-202[4] (Acid baseline)	81	4	201	3
	83	4	203	2
	85	4	205	2
	87	4	207	3

Notes:
1. A rating of 4 is considered cause for rejection.
2. The coupons tested with reagent water showed significant discoloration and dark spots all over the surface (rating: 3).
3. On non-clad material, all acid strippers produced more severe corrosion than did the reagent water.
4. The most severe corrosion was produced by Cee-Bee A-202 (the acid methylene chloride baseline).

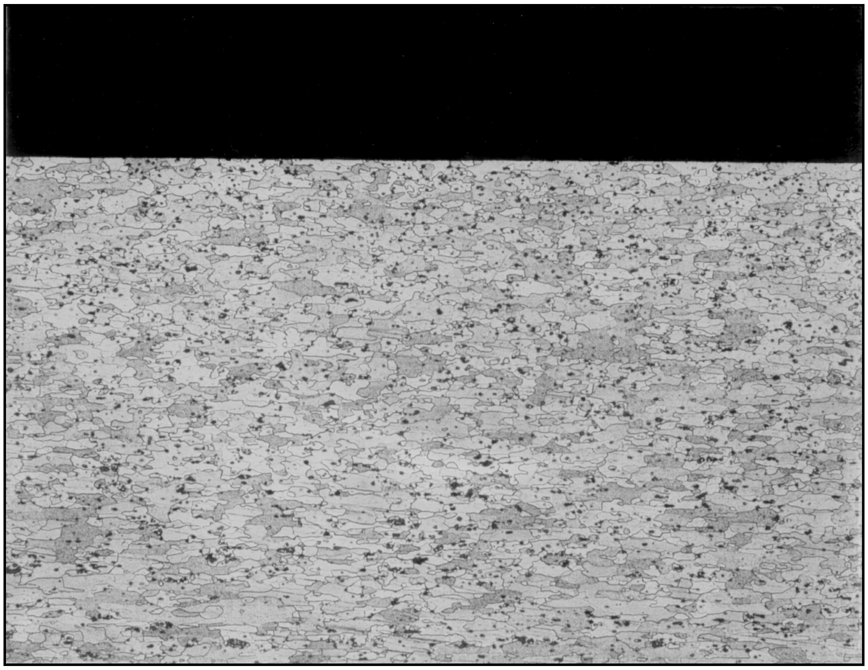


(a) 100x Magnification

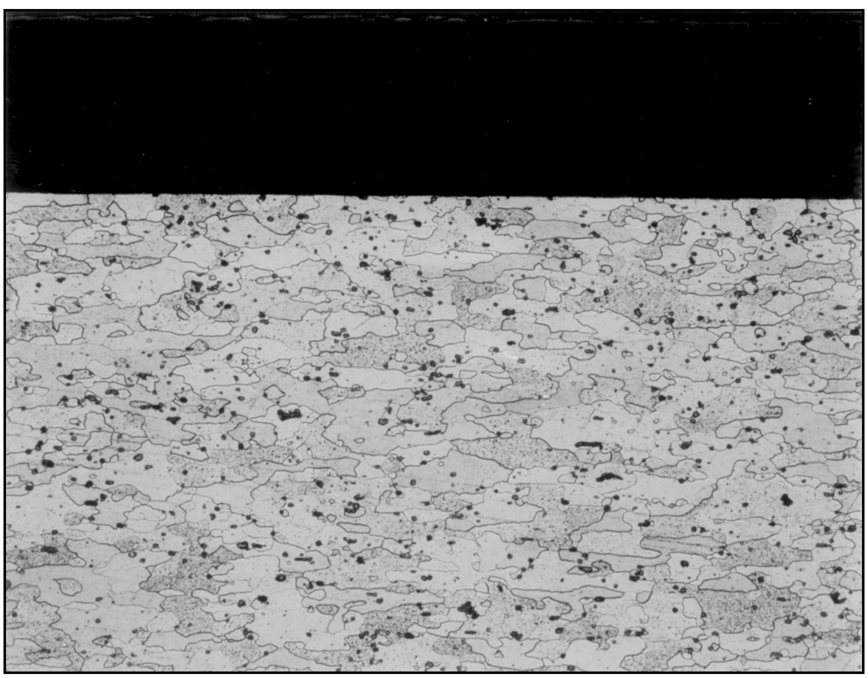


(b) 200x Magnification

Figure 4.2-1. Metallographic Views of Non-Clad 2024-T3 (Plate No. 6) after Sandwich Corrosion Testing with Deionized Water

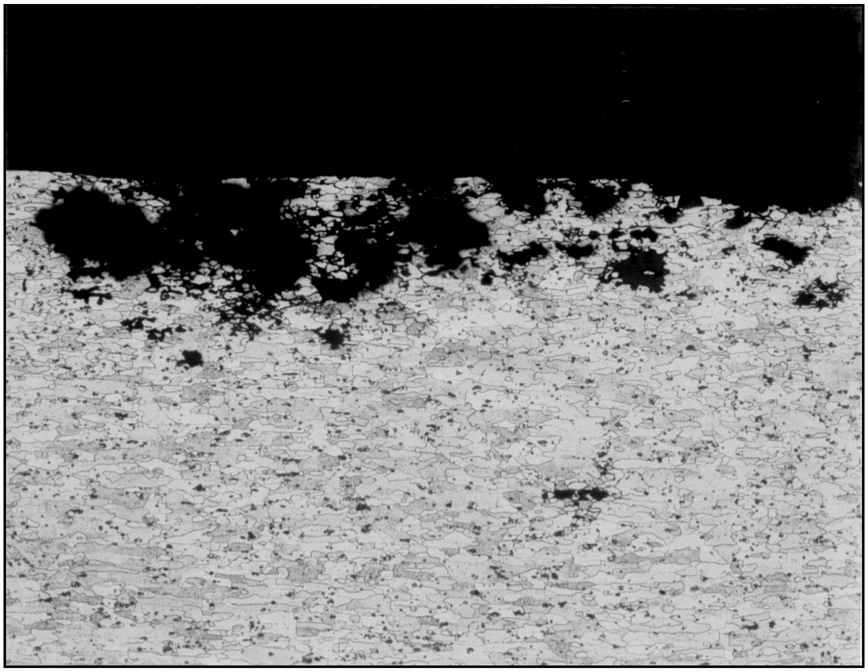


(a) 100x Magnification

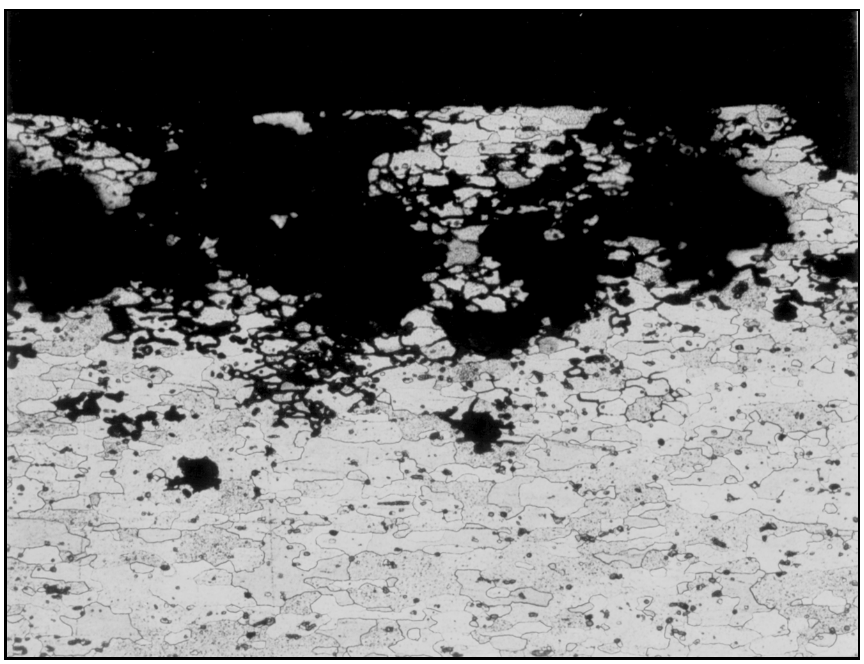


(b) 200x Magnification

Figure 4.2-2. Metallographic Views of Non-Clad 2024-T3 (Plate No. 14)
after Sandwich Corrosion Testing with Turco 6813 (Alkaline)



(a) 100x Magnification

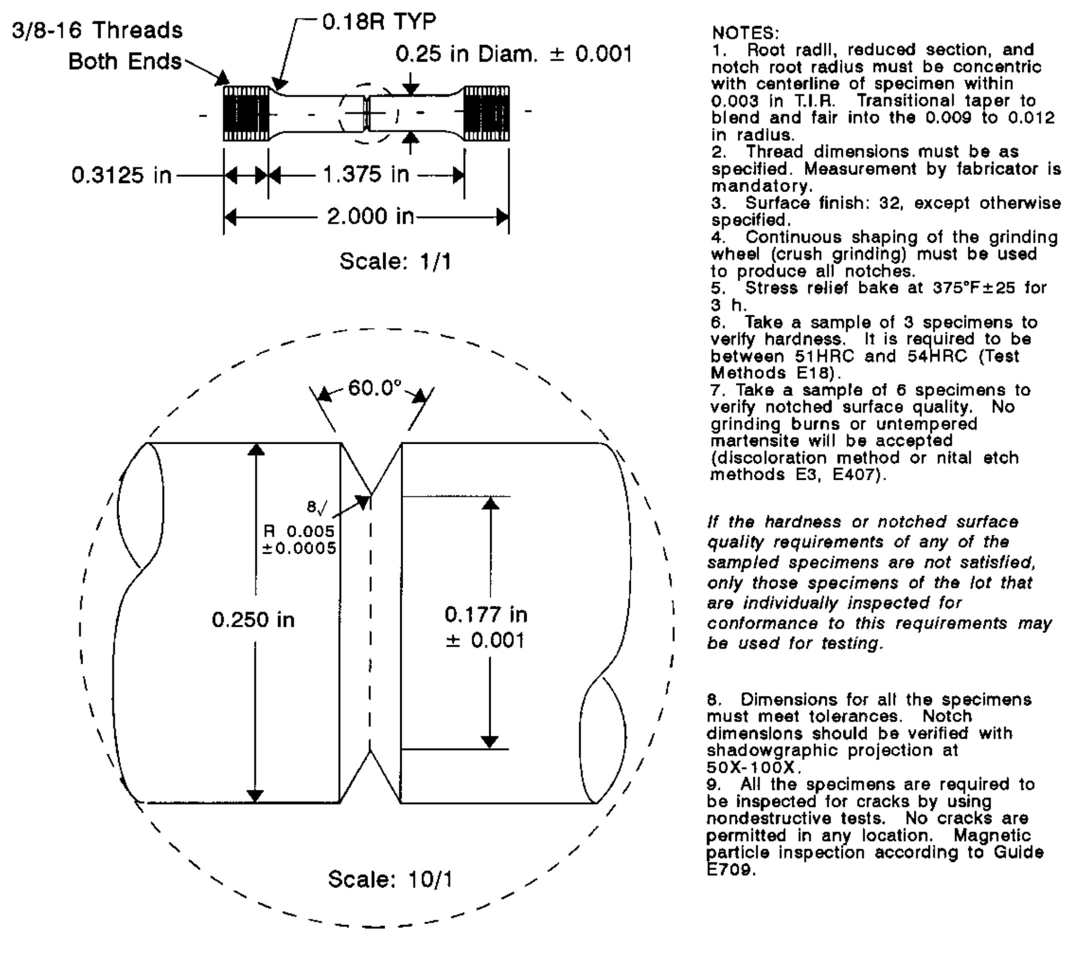


(b) 200x Magnification

Figure 4.2-3. Metallographic Views of Non-Clad 2024-T3 (Plate No. 78) after Sandwich Corrosion Testing with Cee-Bee E-1004B (Acid)

4.3. Hydrogen Embrittlement Mechanical Testing (ASTM F519-93)

Hydrogen embrittlement testing was performed to determine the potential of environmentally advantaged chemicals to introduce hydrogen into high-strength steels. Notched round tensile specimens were fabricated in accordance with ASTM F519, Type 1A (Figure 4.3-1). Specimens were fabricated from American Iron and Steel Institute (AISI) E4340 steel that was heat treated per MIL-H-6875 to obtain a hardness of 51 to 54 HR_C with an ultimate tensile strength of 1800 to 1930 MPa (260 to 280 ksi). This material at this hardness is assumed to be the worst case for this method. The test fixtures were also fabricated from AISI E4340 steel and heat treated to obtain a hardness of 40 to 43 HR_C. Fixtures and specimens were machined from AISI E4340 steel to minimize any polarization effects or galvanic coupling that would influence results.



Notched Round Tensile Specimen (English Units)

Figure 4.3-1. Notched Round Tensile Specimen
for Hydrogen Embrittlement Testing

To determine the material's sensitivity to hydrogen, six of the specimens were exposed to two different embrittling environments before testing. Three specimens were electroplated under the highly embrittling conditions produced in a cadmium cyanide bath (Treatment A in Table 4.3-1.) The other three specimens were electroplated under less embrittling conditions (Treatment B in Table 4.3-1.) All six specimens were loaded to 75% of the notched ultimate tensile strength. The three specimens plated by Treatment A failed within 24 hours (after 2, 10, and 30 minutes), and none of the three specimens plated by Treatment B failed within 200 hours; therefore, this lot of 4340 steel is considered to be of suitable sensitivity.

Table 4.3-1. Conditions for Hydrogen Sensitivity Testing (per Federal Specification QQ-P-416)

Electroplating Bath Composition	Treatment A	Treatment B
Cadmium (AsCdO)	4.5 oz/gal (33.7 g/L)	4.5 oz/gal (33.7 g/L)
Sodium cyanide (NaCN)	14 oz/gal (104 g/L)	14 oz/gal (104 g/L)
NaCN/CdO ratio	3	3
pH	12	12
Temperature	70 to 90 °F (21 to 32 °C)	70 to 90 °F (21 to 32 °C)
Sodium hydroxide (NaOH)	2.5 oz/gal (18.7 g/L)	2.5 oz/gal (18.7 g/L)
Brightener (Rohco 20 X L)	2.0 oz/gal (15.0 g/L)	n/a
Electroplating current	10 A/ft^2 (108 A/m^2)	60 A/ft^2 (645 A/m^2)
Electroplating time	30 min	6 min
Baking temperature	Do not bake.	375 ± 25 °F (190 ± 14 °C)
Baking time	Do not bake.	23 hr

After machining, the remaining notched round tensile specimens used to evaluate the chemicals were degreased and dry abrasive blasted with alumina. Once free of abrasive, the specimens were rinsed with tap water and, while wet, immediately electroplated using a low-embrittlement cadmium cyanide bath (Table 4.3-1, Treatment B). The cadmium-electroplated specimens were rinsed with tap water and rinsed by immersion and swirling for 15 seconds in a solution with a concentration equivalent to 5 pounds (2.3 kg) of chromic acid in 10 gallons (38 L) of water. Chromic acid was removed from the specimens by rinsing with cold tap water, followed by rinsing with hot tap water and drying. These specimens were placed in an oven at 375 ±25 °F (191 ±14 °C) for 23 hours.

Each chemical was tested in the as-received condition at 68 to 86 °F (20 to 30 °C). The containment chamber was isolated around the test specimens. Three specimens per chemical (30 total) were assembled and placed in tension to 45% of the notched ultimate tensile strength. The loaded specimens were immersed in the chemicals in triplicate, and the time to failure was recorded. Tests were discontinued after 150 hours.

A chemical is considered non-embrittling under the conditions tested if no specimens fail within 150 hours after immersion in the chemical at 45% of the notched ultimate tensile strength. A chemical is considered embrittling under the conditions tested if two or more break within the 150-hour control period.

The specimens were loaded in a constant strain load frame, and initial extensometer measurements were taken. Employing a constant strain test, rather than the constant load test recommended in the specification, allowed us to perform several tests simultaneously. A schematic of the load frame and tensile coupon is shown in Figure 4.3-2.

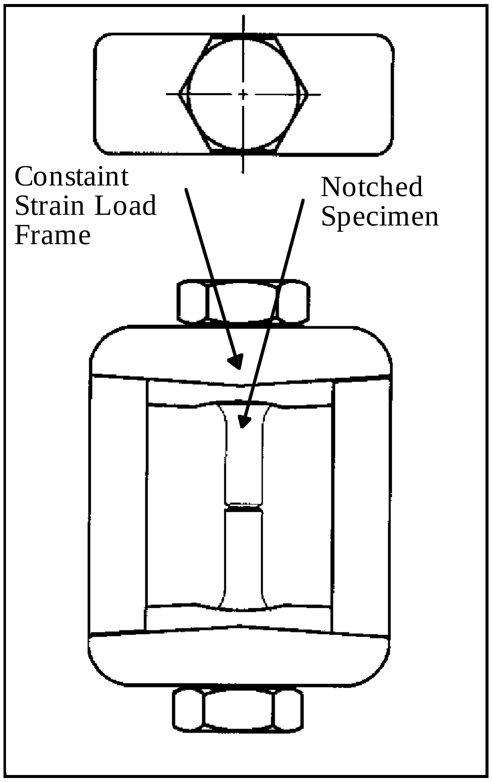


Figure 4.3-2. Schematic Diagram of Notched Round Tensile Specimen and Frames for Hydrogen Embrittlement Testing

To ensure that proper load was maintained, an extensometer was placed across each non-failed specimen before unloading (after the test was complete). These measurements were compared to the initial extensometer measurements to confirm that no load relaxation occurred during the test.

Results of the hydrogen embrittlement testing are presented in Table 4.3-2. Numbers listed in parentheses represent the time interval in which the specimen failed. The failure ratio is the number of specimens that failed over the number of specimens tested under the same conditions.

Table 4.3-2. Results of the Hydrogen Embrittlement Test

Chemical Tested	Failure Ratio	Time to Failure (hr)
Turco 6813 (Alkaline)	0/3	No Failures
Turco 6813-E (Alkaline)	0/3	No Failures
Turco 6840-S (Alkaline)	0/3	No Failures
Stingray 874B – Group 1 (Neutral)	2/3	(98-145), (128-143)
Stingray 874B – Group 2 (Neutral)	1/3	(191-198)
Cee-Bee R-256 (Alkaline baseline)	0/3	No Failures
Turco 6776 (Acid)	3/3	4.5, 6, (28-48)
EZE 540 (Acid)	3/3	0.5, (8-24), (8-24)
PR-2002 (Acid)	3/3	0.5, (7-23), (31-47)
Cee-Bee E-1004B (Acid)	3/3	1.75, 1.75, 1.75
Cee-Bee A-202 (Acid baseline)	3/3	0.5, 0.5, 0.5

The acidic chemicals, including the methylene chloride baseline, failed this test: all acidic chemical specimens failed within 48 hours of exposure. All of these specimens, however, exhibited average failure times exceeding the methylene chloride baseline. Scanning electron microscopy of failure surfaces revealed a large region of intergranular fracture. Metallographic cross sectioning of these samples revealed secondary cracking below the failure surface indicative of grain boundary attack.

Two of three specimens tested in the neutral chemical (Group 1) failed between 98 and 145 hours. Microscopy and metallography of these specimens also revealed a region of the failure surface that exhibited an intergranular fracture with secondary cracking. The remaining specimen that passed the test was loaded to failure and exhibited a ductile failure surface. Three additional samples of the neutral chemical were then tested and are listed in Table 4.3-2 as Group 2 specimens. All of these specimens met the 150-hour exposure requirement. The exposure time for the Group 2 specimens was extended to 200 hours with one specimen failing after 191 hours. The reason for the Group 1 and Group 2 failures for the neutral chemical may be related to the pH of the chemical. The pH of the neutral chemical was measured as 5.7, in contrast to the manufacturer's reported pH of 6.5. The lower pH of the chemical as tested may be responsible for the failures in the neutral Group 1 and Group 2 specimens.

All specimens tested in the alkaline chemicals passed the test with no failures noted. Test specimens loaded to failure after the test exhibited ductile failure surfaces.

4.4. Fatigue Life Testing (SAE MA4872)

Tests are being performed to determine how each stripping process impacts fatigue life. (This evaluation's scope is limited to Type II specimens.) Testing will be performed on clad and non-clad 2024-T3 aluminum sheets with thicknesses of 0.016 and 0.032 inches. Individual sheets of material were identified, and baseline specimens were cut from each sheet. Control panels were identified for each sheet for fatigue testing after being depainted five times. The test results will then be compared to baseline results.

Several steps have been implemented to improve consistency in the baseline fatigue data. New inserts have been installed in the test machine. A series of longitudinal strain gauges was used to instrument a test specimen, which has been used to develop a methodology to ensure uniform stress distribution when specimens are loaded into the test machine. Specimens are being hand-sanded around the edges to minimize crack initiation along the sides of the specimens.

Constant amplitude tension fatigue testing is being performed at a maximum stress of 45 ksi, a stress ratio of R=0.1, and a frequency of 10 Hz. Test data for fatigue specimens from three test panels are shown in Figure 4.4-1.

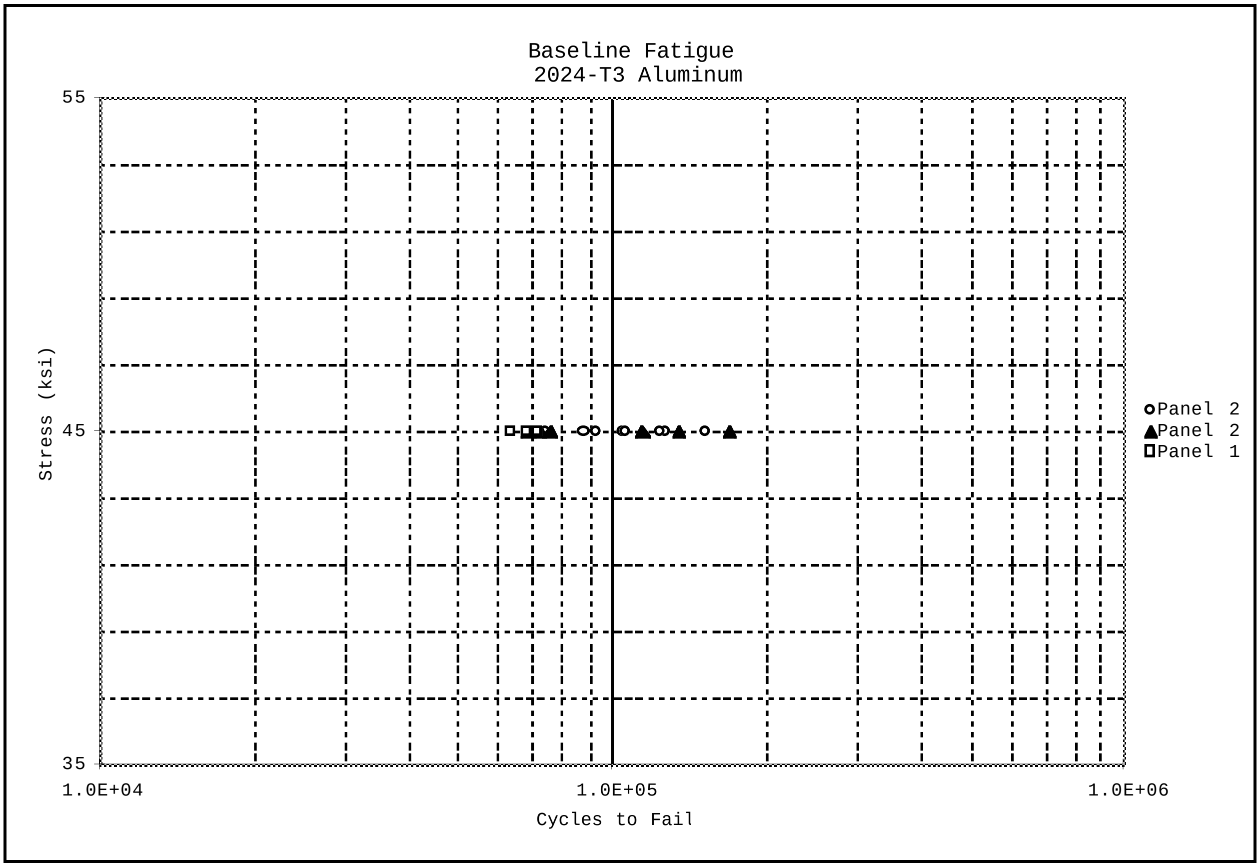


Figure 4.4-1. Baseline Fatigue Data, 2024-T3 Aluminum

4.5. Crack Detectability Testing (SAE MA4872)

The media blast processes (sodium bicarbonate wet stripping, PMB, WaterJet, and ENVIROSTRIP® wheat starch) will undergo crack detectability testing to determine whether their effects might inhibit the detection of substrate cracks. The 48 crack-detectability specimens (4 inches wide by 12 inches long) were cut from the same clad and non-clad 2024-T3 aluminum sheets (0.064 inch thick) as the other media blast process panels. After the panels were painted for the first time and cured for 24 hours at an elevated temperature [50 ±3 °C (122 ±5 °F)], the specimens were precracked using low stress intensities (less than 15 ksi√in.) to minimize plastic deformation at the crack tip. Cracks were then grown at least 1 inch out of each side of electro-discharge machined (EDM) notches, and initial crack length measurements were made on each specimen, using high-frequency eddy current. Figure 4.5-1 shows a precracked, painted sample.

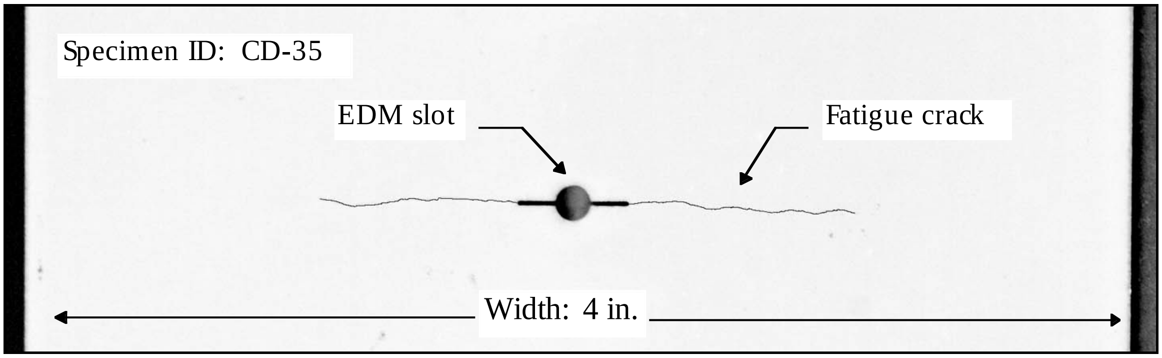


Figure 4.5-1. Crack Detectability Test Specimen

Crack length will be measured again in each cycle after the test specimens have been depainted. The same inspector will make the initial and final crack length measurements. Crack length measurements after each depainting cycle then will be compared to the initial crack length measurements to assess crack closures and/or reductions in crack detectability**.**

APPENDICES

APPENDIX A.1. Excerpt from ISO/SAE MA4872 (Draft 4, pp. 27-28)

SAE MA4872

APPENDIX C
TEST PANEL PREPARATION

C.1 SUBSTRATE:

Test panels shall be 100 mm x 150 mm x 1.6 mm (4 in x 6 in x 0.040 in) 2024-T3 clad aluminum unless otherwise specified in the test method.

C.2 PRETREATMENT:

Test panels shall be degreased and have a chromate conversion coating applied in accordance with prEN 2334 or MIL-C-5541.

C.3 PAINT SYSTEM:

C.3.1 Standard:

a. The paint system shall consist of a layer of MIL-P-23377 epoxy primer and a layer of MIL-C-83286 polyurethane enamel (or primer and enamel in accordance with equivalent commercial aircraft specifications).

b. The dry film thickness of primer shall be 15 to 20 microns (0.6 to 0.8 mils) and the enamel shall be 40 to 60 microns (1.6 to 2.4 mils).

C.3.2 Barrier/Intermediate Coat System:

a. The paint system shall consist of a layer of primer, intermediate coat, and polyurethane enamel in accordance with TNA.007.10028 or TH33.0155 (or equivalent commercial aircraft specification).

b. The dry film thickness of the primer shall be 15 to 20 microns (0.6 to 0.8 mils), intermediate coat shall be 8 to 12 microns (0.3 to 0.5 mils), and the enamel shall be 40 to 60 microns (1.6 to 2.4 mils).

C.4 APPLICATION:

a. The paint system shall be spray applied at 23 °C ± 2 °C (75 °F ± 5 °F) and 50% RH ± 5% RH.

b. Allow the primer to dry 2 to 6 h prior to applying the enamel.

c. Test panels shall be cured at 23 °C ± 2 °C (75 °F ± 5 °F) and 50% RH ± 5% RH for a minimum of seven days before artifical aging or testing.

C.5 ARTIFICAL AGING:

a. Preliminary Screening Tests:

(1) Age panels for 750 h at 50 °C (122 °F) and 95% RH

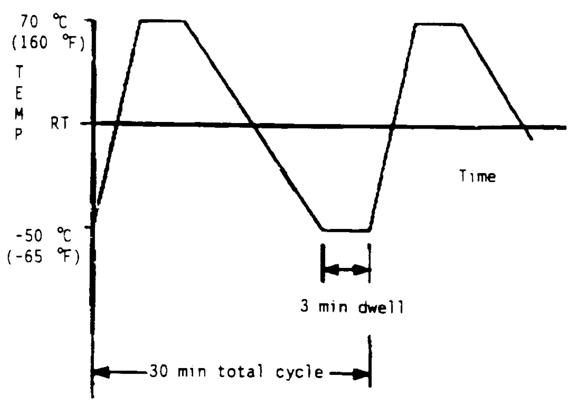
SAE MA4872

C.5 (Continued):

b. Qualification Tests:

(1) Age panels in accordance with Figure C1.

c. Test panels shall be cooled to ambient temperature prior to being stripped.



1. Precondition panels for 12 h at 50 °C ± 2 °C (120 °F ± 5 °F) and 95% relative humidity.
2. Discontinue humidity control, decrease temperature to -50 °C ± 2 °C (-65 °F ± 5 °F), and hold for 1 h.
3. Thermally cycle panels from -50 °C ± 2 °C to 70 °C ± 2 °C (-65 °F ± 5 °F to 160 °F ± 5 °F) for a total of 400 cycles as shown at left.
4. Return chamber to ambient temperature, and repeat steps 1 to 3 above.

FIGURE C1 - Thermal Cycle Artificial Aging

C.6 REAPPLICATION OF PAINT:

a. The painting, stripping, and aging process shall be repeated until the panel has been stripped a minimum of five cycles unless otherwise specified by the appropriate test method.

b. Reapply the paint system in accordance with C.3 and C.4. Conversion coating application shall be reapplied except when the primer layer is left intact.

APPENDIX A.2. Depainting Processes and Results (Sequence 3)

APPENDIX A.2.1. Chemical Stripping (Sequence 3)

Paint System:	Epoxy primer, 0.6 to 0.9 mil thick (MIL-P-23377F, Type 1, Class 2) Polyurethane topcoat, 1.7 to 2.3 mil thick (MIL-C-85285B)
Test Specimens:	Clad and non-clad 2024-T3 aluminum (0.064-in. substrates) in the form of 12-in. by 12-in. control panels
Area Stripped:	144 in.^{2}
Application Methods:	Spray on and brush on
Dwell Time:	4 min to 5 hr
Effectiveness:	Removed up to 100% topcoat and up to 100% primer
MSFC Points of Contact:	EH33/Robin Broad at (256) 544-7016 and EH33/Regina Moore at (256) 544-8456

Table A.2.1-1. Results for Chemical Stripping (Sequence 3)

Substrate Thickness	Panel Number	Chemical Product	Avg. Temperature/ Relative Humidity	Time to Strip	Average Surface Roughness (µin.)		
					Baseline	After Stripping	After Cleaning
0.064 in. (non-clad)	I-1.2.1	Turco 6813	80 °F / 42%	4 hr	3.6	11.8	13.0
	I-1.2.2	Turco 6813	80 °F / 42%	4 hr	3.3	10.6	11.6
	I-1.5.1	Turco 6840S	80 °F / 30%	5 hr	3.6	14.2	14.0
	I-1.5.2	Turco 6840S	80 °F / 30%	5 hr	3.6	13.5	12.6
	I-1.6.2	Stingray 874B	81 °F / 33%	5 hr	3.1	7.1	6.5
	I-1.7.1	Turco 6813E	75 °F / 49%	2 hr, 30 min	4.0	12.6	12.4
	I-1.7.2	Turco 6813E	75 °F / 49%	2 hr, 30 min	4.3	8.35	9.3
	I-2.11.1	EZE 540	82 °F / 31%	2 hr, 30 min	1.5	12.4	10.8
	I-2.11.2	EZE 540	82 °F / 31%	2 hr, 30 min	1.3	12.6	11.8
	I-2.12.1	PR-2002	82 °F / 31%	3 hr, 30 min	1.9	11.7	11.0
	I-2.12.2	PR-2002	82 °F / 31%	3 hr, 30 min	1.4	12.3	12.0
	I-2.14.1	Cee-Bee E-1004B	81 °F / 28%	3 hr, 30 min	1.5	11.8	13.0
	I-2.14.2	Cee-Bee E-1004B	81 °F / 28%	3 hr, 30 min	1.4	13.1	15.7
	I-2.15.3	Stingray 874B	81 °F / 33%	5 hr	1.4	6.3	7.3
	I-2.16.1	Turco 6776	77 °F / 37%	2 hrs, 30 min	1.5	9.8	11.0
	I-2.16.2	Turco 6776	77 °F / 37%	2 hrs, 30 min	1.3	12.0	12.8
	I-2.17.1	Cee-Bee A-202	76 °F / 41%	4 min	1.5	11.8	11.4
	I-2.17.2	Cee-Bee A-202	76 °F / 41%	4 min	1.5	11.2	11.8
	I.2.20.1	Cee-Bee R-256	76 °F / 41%	5 min	1.4	14.2	17.3
	I.2.20.2	Cee-Bee R-256	76 °F / 41%	5 min	1.2	12.0	10.6
0.064 in. (clad)	I-7.1.1	Stingray 874B	81 °F / 33%	5 hr	1.0	17.0	7.7
	I-7.1.2	Stingray 874B	81 °F / 33%	5 hr	1.0	7.7	9.3
	I-7.2.1	Turco 6813	80 °F / 42%	4 hr	1.3	7.9	8.3
	I-7.2.2	Turco 6813	80 °F / 42%	4 hr	1.4	7.7	10.0
	I-7.5.1	Turco 6840S	80 °F / 30%	5 hr	1.4	10.9	14.0
	I-7.5.2	Turco 6840S	80 °F / 30%	5 hr	1.3	10.9	10.6
	I-7.6.2	Stingray 874B	81 °F / 33%	5 hr	1.3	15.0	13.0
	I-7.7.1	Turco 6813E	75 °F / 49%	2 hr, 30 min	2.6	9.1	9.6
	I-7.7.2	Turco 6813E	75 °F / 49%	2 hr, 30 min	1.3	8.2	9.1
	I-7.8.2	Turco 6840S	80 °F / 30%	5 hr	1.2	9.5	9.8
	I-7.9.1	Turco 6813E	75 °F / 49%	2 hr, 30 min	1.0	8.5	7.3
	I-7.9.2	Turco 6813	80 °F / 42%	4 hr	1.0	9.9	9.4
	I-7.10.1	Cee-Bee R-256	76 °F / 41%	5 min	1.2	6.9	6.3
	I-7.11.1	EZE 540	82 °F / 31%	2 hr, 30 min	1.3	8.5	8.7
	I-7.11.2	EZE 540	82 °F / 31%	2 hr, 30 min	1.0	9.0	8.5
	I-7.12.1	PR-2002	82 °F / 31%	3 hr, 30 min	0.9	6.3	6.9
	I-7.12.2	PR-2002	82 °F / 31%	3 hr, 30 min	1.2	9.5	12.2
	I-7.13.1	EZE 540	82 °F / 31%	2 hr, 30 min	1.1	10.6	11.8
	I-7.13.2	PR-2002	82 °F / 31%	3 hr, 30 min	1.2	8.4	9.6
	I-7.14.1	Cee-Bee E-1004B	81 °F / 28%	3 hr, 30 min	1.0	11.8	12.2
	I-7.14.2	Cee-Bee E-1004B	81 °F / 28%	3 hr, 30 min	1.3	6.9	7.7
	I-7.15.1	Turco 6776	77 °F / 37%	2 hrs, 30 min	1.2	7.9	9.3
	I-7.15.2	Turco 6776	77 °F / 37%	2 hrs, 30 min	1.2	10.2	10.2
	I-7.17.1	Cee-Bee A-202	76 °F / 41%	4 min	1.3	9.3	9.8
	I-7.17.2	Cee-Bee A-202	76 °F / 41%	4 min	1.2	7.7	10.2
	I-7.18.1	Cee-Bee E-1004B	81 °F / 28%	3 hr, 30 min	1.0	9.6	8.1
	I-7.18.2	Turco 6776	77 °F / 37%	2 hrs, 30 min	1.1	9.6	8.5
	I-7.20.1	Cee-Bee R-256	76 °F / 41%	5 min	1.1	10.9	10.4
	I-7.20.2	Cee-Bee R-256	76 °F / 41%	5 min	1.0	10.6	13.2
	I-7.21.1	Cee-Bee A-202	76 °F / 41%	4 min	1.2	12.3	8.5

Note: Cee-Bee A-202 and R-256 are methylene chloride products being used as baselines.

APPENDIX A.2.2. CO_2 Blasting *(discontinued)*

(Note: After Sequence 1, testing was discontinued on the TOMCO$_2$ and COLDJET™ systems.)

APPENDIX A.2.3. FLASHJET® Coating Removal (Sequence 3)

Paint System:	Epoxy primer, 0.6 to 0.9 mil thick (MIL-P-23377F, Type 1, Class 2) Polyurethane topcoat, 1.7 to 2.3 mil thick (MIL-C-85285B)
Test Specimens:	Non-clad 2024-T3 aluminum (0.016-, 0.051-, and 0.064-in. substrates) in the form of 22-in. by 22-in. control panels (0.016-, 0.051-, and 0.064-in. substrates) and 12-in. by 12-in. control panels (0.064-in. substrates)
Area Stripped:	484 $in.^2$ (each 0.016-in. substrate, 22-in. by 22-in. panels) 484 $in.^2$ (each 0.051-in. substrate and one 0.064-in. substrate, 22-in. by 22-in. panels) 144 $in.^2$ (five 0.064-in. substrates, 12-in. by 12-in. panels)
Angle of Attack:	21 to 29°
Stand-off Distance:	2 to 3 in.
Media Flow Rate:	500 to 1000 lb/hr
CO_2 Input Pressure to Nozzle:	90 to 180 psi
Input Voltage:	1900 to 2300 V
Repetition Rate:	3 to 5 flashes/sec
Translational Velocity:	0.75 to 1.4 in./sec
Stripping Passes:	6 to 22, but not over the same path
Effectiveness:	Removed up to 99% topcoat and 57 to 74% primer (Boeing-St. Louis recommends leaving some degree of primer intact on substrates.)
Notes:	Under “Stripping Passes,” note that all passes were not made over the same path. The panels averaged 8 passes to primer and 4 passes to substrate.
MSFC Point of Contact:	EH33/Steve Burlingame at (256) 544-8860

Table A.2.3-1. Results for FLASHJET® Coating Removal (Sequence 3)

Substrate Thickness [1] (in.)	Panel Number	Time to Strip (min:sec)	Strip Rate (in.^{2}/min)	Average Surface Roughness (μin.)		
				Baseline	After Stripping	After Cleaning
0.016 (non-clad)	IV-14.1	7:10	67.5	2.1	18.4	15.0
	IV-14.2	6:18	76.8	2.1	19.7	14.2
	IV-14.3	5:02	96.2	2.1	21.4	14.3
	IV-15.4	[2]	[2]	2.1	[2]	[2]
	IV-15.5	10:47	44.9	2.1	19.8	15.6
	IV-15.6	5:02	96.2	2.1	23.9	17.2
	IV-15.7	6:00	80.7	2.1	18.9	13.5
	IV-15.8	8:36	56.3	2.1	20.5	14.3
	IV-15.9	7:21	65.9	2.1	19.1	15.3
	IV-15.10	7:16	66.6	2.1	22.2	15.6
	IV-15.11	6:37	73.1	2.1	19.1	13.9
	IV-15.12	8:47	55.1	2.1	22.0	17.3
	IV-16.13	5:58	81.1	2.1	18.4	13.1
	IV-16.14	6:29	74.7	2.1	19.8	13.9
	IV-16.15	5:23	89.9	2.1	23.9	14.3
0.051 (non-clad)	IV-9.1	3:54	124.1	1.6	17.0	17.8
	IV-9.2	3:36	134.4	1.6	18.0	18.0
	IV-9.3	3:36	134.4	1.6	19.4	15.9
	IV-9.5	3:36	134.4	1.6	18.4	15.0
0.064 (non-clad)	IV-3.1	4:48	100.8	1.9	17.2	14.5
	IV-I-1.9.1	1:33	92.9	1.9	18.1	15.9
	IV-I-1.9.2	1:33	92.9	1.9	14.4	14.6
	IV-I-1.9.3	1:34	91.9	1.9	17.3	19.1
	IV-I-1.10.2	1:34	91.9	1.9	16.5	12.2
	IV-I-1.10.3	1:34	91.9	1.9	16.7	14.6

Notes: 1. Control panel dimensions are 22 in. by 22 in. for the 0.016-in. and 0.051-in. substrates. The 0.064-in. substrates consist of five 12-in. by 12-in. control panels (IV-I-1.9.1, IV-I-1.9.2, IV-I-1.9.3, IV-I-1.10-2, IV-I-1.10.3) and one 22-in. by 22-in. control panel (IV-3.1).

2. During Sequence 2, this process overheated several 0.016-in. panels, including IV-14.2, IV-15.4, IV-15.6, IV-15.7, IV-15.8, IV-15.10, IV-15.11, IV-15.12, IV-16.13, IV-16.14, and IV-16.15. Afterward, the most overheated panel (IV-15.4) was cut for materials properties testing; therefore, this panel is no longer available for FLASHJET® processing.

APPENDIX A.2.4. CO_2 Laser Stripping

Sequence 3 results for CO_2 laser stripping will be presented in the final report.

APPENDIX A.2.5. Plastic Media Blasting (Sequence 3)

Paint System:	Epoxy primer, 0.6 to 0.9 mil thick (MIL-P-23377F, Type 1, Class 2) Polyurethane topcoat, 1.7 to 2.3 mil thick (MIL-C-85285B)
Test Specimens:	Non-clad 2024-T3 aluminum in the form of 22-in. by 22-in. control panels (0.016- and 0.051-in. substrates) and 12-in. by 12-in. control panels (0.064-in. substrates);.clad 2024-T3 aluminum in the form of 22-in. by 22-in. control panels (0.016- and 0.032-in. substrates)
Area Stripped:	484 in.^{2} (0.016-, 0.032-, and 0.051-in. substrates) 144 in.^{2} (0.064-in. substrate)
Nozzle:	Inside diameters of 0.5 in. at throat and 1.0 in. at exit
Stand-off Distance:	8 to 12 in.
Angle of Attack:	30° (0.016-, 0.032-, and 0.051-in. substrates) 30 to 45° (0.064-in. substrates)
Mesh Size:	Mixture of 20/30 (80%) and 16/20 (20%)
Media Flow Rate:	250 to 500 lb/hr
Pressure:	30 psi (0.016-in. substrates) 35 psi (0.032- and 0.051-in. substrates) 40 psi (0.064-in. substrates)
Stripping Passes:	1
Effectiveness:	Removed 100% topcoat and ~80% primer
Notes:	Strip rates were improved by increasing the flow rate of the plastic media, as well as by adding larger 16/20 mesh media to the smaller 20/30 mesh media to increase process aggressiveness. Bending was noted when the 0.016-in. substrates were stripped at pressures >30 psi. In Sequence 3, we used a venturi nozzle with inside diameters of 0.5 in. at the throat and 1.0 in. at the exit, which is more representative of PMB nozzles used in the field. This change increased the strip rate. The previous 3- to 5-in. stand-off distance was increased to 8 to 12 in.
MSFC Point of Contact:	EH33/Johnnie Clark at (256) 544-2799

Table A.2.5-1. Results for Plastic Media Blasting - Non-Clad (Sequence 3)

Substrate Thickness (in.)	Panel Number	Time to Strip (min:sec)	Strip Rate ($in.^2/min$)	Average Surface Roughness (µin.) Baseline	After Stripping	After Cleaning
0.016 (non-clad)	VII-21.28	17:11	28.17	1.1	13.1	11.4
	VII-VIII-29.16	17:18	27.98	1.5	19.2	17.6
	VII-VIII-29.19	18:08	26.70	1.8	21.4	21.1
	VII-VIII-29.20	18:12	26.59	1.7	22.2	20.2
	VII-VIII-29.21	18:43	25.85	1.3	22.7	18.4
	VII-VIII-29.22	17:57	26.96	1.6	23.8	18.4
	VII-VIII-30.24	17:27	27.74	1.7	25.4	21.6
	VII-VIII-30.26	17:33	27.58	1.3	23.9	22.1
	VII-VIII-30.27	18:44	25.84	1.6	20.5	12.9
	VII-VIII-30.28	17:56	26.99	2.1	19.7	14.3
	VII-VIII-30.30	16:57	28.59	1.7	22.8	18.7
	VII-VIII-30.31	18:36	26.02	1.5	16.5	16.4
0.051 (non-clad)	VII-VIII-11.4	14:55	32.44	1.9	27.4	30.1
	VII-VIII-12.1	14:37	33.10	1.4	27.2	22.4
	VII-VIII-12.2	15:09	31.95	1.2	31.7	16.9
0.064 (non-clad)	VII-I-1.1.3	5:11	27.80	3.6	12.4	12.4
	VII-I-1.1.4	4:57	29.09	2.9	13.4	14.0
	VII-I-1.2.3	5:27	26.42	4.1	15.1	12.8
	VII-I-1.2.4	5:36	25.71	3.4	16.1	14.6
	VII-I-1.3.3	5:11	27.80	3.0	16.7	12.4
	VII-I-1.3.4	5:37	25.67	3.7	13.9	16.3
	VII-I-1.4.3	5:07	28.12	3.2	14.6	14.8
	VII-I-1.4.4	5:15	27.43	2.9	17.3	16.0
	VII-I-1.5.3	5:32	26.04	3.1	15.9	16.3
	VII-I-1.5.4	5:11	27.80	2.7	13.1	13.0
	VII-I-1.6.3	4:59	28.92	3.8	10.7	9.8
	VII-I-1.6.4	5:56	24.28	3.9	10.7	11.2
	VII-I-1.7.3	5:21	26.92	3.5	12.1	12.2
	VII-I-1.7.4	5:35	25.81	3.9	16.4	12.6

Table A.2.5-2. Results for Plastic Media Blasting - Clad (Sequence 1)

Substrate Thickness (in.)	Panel Number	Time to Strip (min:sec)	Strip Rate (in.^{2}/min)	Average Surface Roughness (μin.)		
				Baseline	After Stripping	After Cleaning
0.016-inch (clad)	VII-40.1	23:12	20.86	1.1	33.1	38.6
	VII-40.2	22:58	21.07	1.5	38.2	41.3
	VII-40.3	22:47	21.25	1.8	37.4	32.3
	VII-40.4	23:34	20.53	1.7	35.4	42.5
	VII-40.5	23:16	20.80	1.3	32.3	37.0
0.032-inch (clad)	VII-41.1	21:31	22.49	1.6	121.7	116.5
	VII-41.2	22:05	21.92	1.7	107.9	103.9
	VII-41.3	22:47	21.25	1.3	94.9	106.3
	VII-41.4	22:03	21.95	1.6	128.4	111.8
	VII-41.5	22:51	21.18	2.1	151.2	113.8

Table A.2.5-3. Results for Plastic Media Blasting - Clad (Sequence 2)

Substrate Thickness (in.)	Panel Number	Time to Strip (min:sec)	Strip Rate (in.^{2}/min)	Average Surface Roughness (μin.)		
				Baseline	After Stripping	After Cleaning
0.016-inch (clad)	VII-40.1	21:09	22.83	1.1	40.3	23.94
	VII-40.2	20:45	23.50	1.5	42.0	29.29
	VII-40.3	21:33	22.50	1.8	37.6	25.83
	VII-40.4	20:51	23.21	1.7	38.4	26.46
	VII-40.5	21:49	22.19	1.3	42.7	22.68
0.032-inch (clad)	VII-41.1	18:41	25.91	1.6	100.6	70.71
	VII-41.2	19:15	25.14	1.7	82.4	54.80
	VII-41.3	19:36	24.69	1.3	94.0	57.80
	VII-41.4	18:53	25.64	1.6	105.8	57.95
	VII-41.5	19:24	24.95	2.1	87.1	66.61

Table A.2.5-4. Results for Plastic Media Blasting - Clad (Sequence 3)

Substrate Thickness (in.)	Panel Number	Time to Strip (min:sec)	Strip Rate (in.^{2}/min)	Average Surface Roughness (μin.)		
				Baseline	After Stripping	After Cleaning
0.016-inch (clad)	VII-40.1	17:19	27.93	1.1	-	-
	VII-40.2	17:43	27.34	1.5	-	-
	VII-40.3	16:58	28.50	1.8	-	-
	VII-40.4	18:03	26.74	1.7	-	-
	VII-40.5	17:31	27.64	1.3	-	-
0.032-inch (clad)	VII-41.1	16:12	29.96	1.6	-	-
	VII-41.2	16:09	30.01	1.7	-	-
	VII-41.3	15:49	30.61	1.3	-	-
	VII-41.4	15:59	30.25	1.6	-	-
	VII-41.5	16:26	29.45	2.1	-	-

Note: Sequence 3 surface roughness data for the PMB clad panels are unavailable, a result of anomalies in processing.

APPENDIX A.2.6. Sodium Bicarbonate Wet Stripping

Sequence 3 results for sodium bicarbonate wet stripping will be presented in the final report.

APPENDIX A.2.7. WaterJet Blasting

Sequence 3 results for WaterJet blasting will be presented in the final report.

APPENDIX A.2.8. ENVIROSTRIP® Wheat Starch Blasting (Sequence 3)

A.2.8.1 Manual

Paint System:	Epoxy primer, 0.6 to 0.9 mil thick (MIL-P-23377F, Type 1, Class 2) Polyurethane topcoat, 1.7 to 2.3 mil thick (MIL-C-85285B)
Test Specimens:	Non-clad 2024-T3 aluminum (0.016-, 0.051-, and 0.064-in. substrates) in the form of 12-in. by 18-in. control panels
Area Stripped:	216 in.^{2} per panel
Nozzle:	0.5-in. double venturi nozzle
Projection Angle:	30 to 60°
Stand-off Distance:	4 to 8 in.
Mesh Size:	12 to 120
Media Flow Rate:	18 lb/min (0.016-in. substrates) 12 lb/min (0.051- and 0.064-in. substrates)
Pressure:	20 psi (0.016-in. substrates) 30 psi (0.051- and 0.064-in. substrates)
Stripping Width:	0.75 in.
Stripping Passes:	1
Effectiveness:	Removed 100% topcoat and 99% primer
MSFC Point of Contact:	EH33/Steve Burlingame at (256) 544-8860

Table A.2.8-1. Results for Manual Wheat Starch Blasting (Sequence 3)

Substrate Thickness (in.)	Panel Number	Time to Strip (min:sec)	Strip Rate (in.^{2}/min)	Average Surface Roughness (μin.)		
				Baseline	After Stripping	After Cleaning
0.016 (non-clad)	IX-13.1	3:07	69.3	1.2	23.6	18.0
	IX-13.2	2:58	72.8	1.1	17.6	17.2
	IX-13.3	3:29	62.0	1.0	22.8	18.4
	IX-13.4	2:58	72.8	1.1	19.1	15.9
	IX-13.5	2:52	73.4	1.1	16.2	14.2
	IX-13.6	2:51	75.8	1.0	13.9	13.2
0.051 (non-clad)	IX-10.4	2:11	99.0	1.5	22.4	18.3
	IX-10.5	1:56	111.7	1.6	11.5	13.1
0.064 (non-clad)	IX-3.4	2:02	106.4	1.3	16.1	15.1
	IX-3.5	1:52	115.7	2.5	15.0	16.2
	IX-3.6	2:00	108.0	1.3	14.5	17.8

A.2.8.2 Semi-Automatic

Paint System:	Epoxy primer, 0.6 to 0.9 mil thick (MIL-P-23377F, Type 1, Class 2) Polyurethane topcoat, 1.7 to 2.3 mil thick (MIL-C-85285B)
Test Specimens:	Non-clad 2024-T3 aluminum (0.016-, 0.051-, and 0.064-in. substrates) in the form of 12-in. by 18-in. control panels
Area Stripped:	215 in.^{2} (0.016-in. substrates) 216 in.^{2} (0.051- and 0.064-in. substrates)
Nozzle:	4-in. flat nozzle, CAE T-7 (S/N 003)
Projection Angle:	45°
Stand-off Distance:	3 in.
Mesh Size:	12 to 120
Media Flow Rate:	18 lb/min (0.016-in. substrates) 12 lb/min (0.051- and 0.064-in. substrates)
Pressure:	20 psi (0.016-in. substrates) 40 psi (0.051- and 0.064-in. substrates)
Translational Velocity:	1.15 in./sec (0.016-in. substrates) 2.1 in./sec (0.051- and 0.064-in. substrates)
Stripping Width:	4.25 in.
Stripping Passes:	1
Effectiveness:	Removed 100% topcoat and 99% primer
MSFC Point of Contact:	EH33/Steve Burlingame at (256) 544-8860

Table A.2.8-2. Results for Semi-Automatic Wheat Starch Blasting (Sequence 3)

Substrate Thickness (in.)	Panel Number	Time to Strip (sec)	Strip Rate (in.^{2}/min)	Average Surface Roughness (μin.)		
				Baseline	After Stripping	After Cleaning
0.016 (non-clad)	IX-13.7	44	293.3	1.0	13.9	12.8
	IX-13.8	44	293.3	1.0	18.4	16.4
	IX-13.9	44	293.3	1.3	23.5	24.1
	IX-13.10	44	293.3	1.0	19.5	23.6
	IX-13.11	44	293.3	1.0	24.3	26.1
	IX-13.12	44	293.3	1.1	20.8	17.3
	IX-13.13	44	293.3	1.4	18.7	15.0
	IX-13.14	44	293.3	1.2	24.1	14.6
	IX-13.15	44	293.3	1.2	21.7	14.8
	IX-13.16	44	293.3	1.0	15.3	12.9
	IX-13.17	44	293.3	1.2	25.0	27.4
	IX-13.18	44	293.3	1.3	17.2	18.4
	IX-13.20	44	293.3	1.1	15.7	12.0
0.051 (non-clad)	IX-10.1	24.2	535.5	2.4	14.3	14.5
	IX-10.2	24.2	535.5	1.6	14.5	14.5
	IX-10.3	24.2	535.5	1.4	16.5	19.2
0.064 (non-clad)	IX-3.1	24.2	535.5	1.2	17.2	16.9
	IX-3.2	24.2	535.5	1.2	13.1	12.8
	IX-3.3	24.2	535.5	1.3	16.7	12.4